THE CAUSE OF EARTHQUAKES, MOUNTAIN FORMATION AND KINDRED PHENOMENA CONNECTED WITH THE PHYSICS OF THE EARTH.

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I. General Considerations on the Cause of Earthquakes.

§ 1. *Introduction.*

The great San Francisco earthquake of April 18, 1906, presented certain remarkable characteristics which immediately became a subject of investigation on the part of men of science resident in this part of the United States. One very striking feature of this earthquake was the conspicuous rotatory motion of the earth particle; and another was the long duration of the disturbance. The rotatory motion appeared so remarkable and so difficult to reconcile with theories very generally held by geologists and seismologists that it seemed worth while to make a somewhat comprehensive survey of the general subject of earthquakes, in the hope of reaching a better understanding of the cause of these phenomena. And as the details of this particular earthquake will be fully treated by others,[1] the result of the present inquiry[2] into the physical cause of earthquakes

[1] The Committee of Investigation appointed by the Governor of California: Professors A. C. Lawson, George Davidson, A. O. Leuschner, G. K. Gilbert, W. W. Campbell, H. F. Ried, J. C. Branner, Chas. Burkhalter. Investigations are being made also by Professor Omori of the Imperial University of Tokio, Messrs. Otto Von Geldern, Luther Wagoner, and Mr. Hoehl of the American Society of Civil Engineers, and perhaps by others.

[2] Rear Admiral H. H. Rousseau, U. S. Navy, Chief of the Bureau of Yards and Docks, has read this paper throughout, and made a number of suggestions which proved valuable. The independent judgment of an experienced engineer was felt to be no inconsiderable advantage in weighing some of the difficult questions here treated, and my most cordial acknowledgements are due to Rear Admiral Rousseau for his great kindness.

and other related phenomena may not be without interest to investigators of the physics of the earth.

Almost exactly four months after the earthquake of April 18, namely, August 16, 1906, another, much more terrible, laid waste Valparaiso and the surrounding cities of Chili, producing scenes of desolation which are rare—even in South America. The scientific need and the humanitarian demand for an investigation of the cause of these disturbances could, therefore, hardly be greater than it is at the present time. But if it be said that the researches of science are powerless to stay the hand of the destroyer, and only the laws of these terrible phenomena can be discovered, yet even the intelligent appreciation of natural laws may greatly mitigate the extent of the disaster and suffering which follow; and on both humane and scientific grounds, the prospects of extending the domain of useful knowledge furnish a high inspiration for earnest endeavor to penetrate the mystery of these hidden forces of nature, which so long have baffled the skill of philosophers.

Earthquakes and volcanoes were among the earliest physical phenomena to receive the attention of the ancients, and they have always occupied a prominent place in natural philosophy. Although the importance of the subject was derived originally from the terrible disasters which these mysterious agencies of unknown forces occasionally inflict upon large portions of mankind, in more recent times earthquakes have been studied also as about the only available means of throwing light upon the physics of the globe. No artificial forces at the command of the experimenter are great enough to produce vibrations of the earth's crust or to transmit them through the body of the planet when once established in the surface layers.

But notwithstanding all the labor and research which has been bestowed upon the subject, it can hardly be said that we yet have any satisfactory theory of the cause of these phenomena. This is the more regrettable, because, on the one hand, it places it beyond the power of science to predict earthquakes, or even to foretell the regions of their occurrence, which might afford some measure of security to life and property; while, on the other, it leaves many men of science without adequate hope that the true cause of these phenomena will ever be discovered, and at the same time so completely bewildered by a multitude of unsatisfactory theories that the progress of discovery itself is seriously embarrassed.

There will naturally be those who doubt the existence of one common and universal cause of earthquake and volcanic phenomena. Nevertheless, difficult as the subject is, we believe that such a cause exists, and that it is capable of demonstration, if not with mathematical rigor at least with such high degree of probability[1] as to render the resulting theory practically useful, and we ask nothing of the reader except a careful examination of the facts as interpreted in the light of the cause assigned in this paper. If such a view, associating the varied phenomena of earthquakes and volcanoes, with mountain formation and the development of great sea waves, under one common cause, renders them more intelligible, and enables us to see the relations of all the observed phenomena in a clearer and simpler light, there will be presumptive evidence of the truth of the proposed theory; and the probability of its correctness will increase with the harmony existing among all the known facts, and the effectiveness with which contradictions of other theories may be established. The final test of the theory will depend upon its usefulness in the advancement of discovery, so as to harmonize the whole body of earthquake and volcanic phenomena, including those associated with the origin and structure of mountains, the observations of geodesy, and of great sea waves, in their mutual relations, and in respect to the undisturbed parts of our globe. If the theory shall meet this test satisfactorily, we may feel confident that it assigns the true cause of the phenomena, and within certain limits the resulting laws of nature may be used to foretell events which will contribute to the repose and safety of mankind, and to the progress and usefulness of discovery in this interesting branch of natural philosophy.

§ 2. *The dynamical cause of earthquakes and volcanoes probably*

[1] The unequivocal proof of the elevation of the coast at Yakutat Bay, Alaska, Sept. 10–15, 1899, seems to remove the last trace of uncertainty regarding the chief function of earthquakes, and makes the demonstration as rigorous as that of any theorem in geometry. See the important memoir of Tarr and Martin, Bulletin of the Geological Society of America, vol. 17, May, 1906. Professor George Davidson, President of the Seismological Society of America, kindly called my attention to this classic work after the present investigation was finished. Note added December 12, 1906.

depends upon the explosive power of steam formed within or just beneath the heated rocks of the earth's crust chiefly by the leakage of the ocean beds.

Some of the most complicated phenomena in nature depend upon the simplest and most obvious of causes, but there are several reasons why the true cause often proves very difficult to discover. On the one hand our mental operations are not infrequently thwarted by conflicting prejudices and contradictory theories, so that attention is diverted from the real questions; and, on the other, our clearness of vision and power of intuition are blinded by the very closeness and familiarity of the true cause, which is least suspected. Success in interpreting nature depends upon a combination of the proper elements of thought into one simple connected view which deals not with details but with the general tendencies. In the case of earthquakes and volcanoes this general view has been very difficult to obtain; and with the growth of elaborate scientific investigation and classification of earthquakes the difficulty has increased rather than diminished. For attention has been given to the attainment of high accuracy in the measurement of tremors by seismographs and other apparatus, and investigators have been occupied with the registration and discussion of the details of phenomena rather than with the general underlying causes.

We shall hereafter examine the porosity of matter and the problem of the penetration of water into the rocks of the earth's crust, both from the experimental and historical standpoints, but let us first consider the probable state of the internal heat of the earth. In *Astron. Nach.*, No. 4053, the writer has shown that when we consider the force of gravity alone, and suppose a body to be made up of gas reduced to the state of single atoms, over one-half of the primordial supply of heat is stored up within the condensing mass, while still in the gaseous stage; and in a later paper on the rigidity of the heavenly bodies (*A. N.*, 4104), it is shown that circulation and radiation become retarded and greatly restricted with increasing density, so that in the later stages of the development of a mass like the earth, much more than one-half of the heat generated is retained within the mass for raising the temperature. It is shown that all the heat of our earth depending on gravitation would raise the temperature of an equal mass of water 9954° C.; and as decidedly more than half of it is still retained in the globe, we may conclude that the internal heat of the earth is ample to raise the whole globe to a temperature of something like 20,000° or 25,000° C., according to the average specific heat of the earth's matter. If radium and other related elements exist within the earth in appreciable quantities, the amount of heat stored up, as Sir G. H. Darwin and others[1] have remarked, may be vastly greater yet. Now it is recognized that the crust or cooled layer on the outside of our planet is extremely thin, and we know that the temperature increases downward at an average rate of something like 1° C. for each 30 metres of descent. This accords also with Lord Kelvin's calculations on the cooling of a molten globe, carried out in conformity with Fourier's Analytical Theory of the propagation of heat in solid bodies.[2]

From this we may infer, as geologists have long since remarked, that, even without the penetration of steam, molten rock would be encountered at a depth of decidedly less than 30 kilometres. As the percolation of hot water and steam appreciably lowers the melting point of silicious and perhaps other rocks (the lavas are mainly silicates), and itself develops at the very low temperature of only 100° C. under atmospheric pressure, we may infer that it would form in the earth at a depth much smaller than 30 kms. At no more than 10 or 15 kms. under the ocean beds large quantities of it might be produced and give rise to imprisoned forces of tremendous power. Besides it would rapidly absorb and spread in the hotter layers of rock beneath, just as in the case of gases absorbed in hot steel, cited by Tait and quoted in § 5. That this absorption actually takes place is proved by the vast clouds of steam given off by melted lava after it pours from a volcano, such as Vesuvius.

We are thus confronted with the following situation:

The internal temperature of the earth is extremely high, with

[1] Presidential address to the British Association for the Advancement of Science, Capetown, 1905; also a very recent paper presented to the Royal Society, April 5, 1906, by the Hon. R. J. Strutt, F.R.S., reported in *Nature* of May 17, 1906.

[2] "The Secular Cooling of the Earth," Appendix D, Thomson and Tait's "Nat. Phil."

FIG. 1.

Mt. Pelée. The burning cloud of December 16, 1902, seen from the sea. (From the Belgian Astronomical Society, tenth year. Plate V.)

heated rocks quite near the surface, while the crust is fractured and leaky everywhere, and especially where the depth of the sea is greatest. The sea covers three-fourths of the earth's surface, and earthquakes are found to be most violent where the sea is deepest, *and volcanoes most numerous on the adjacent shores. Could then anything be more probable than to suppose that both of these great natural phenomena depend simply and wholly upon the explosive power of steam which has developed in the heated rock of the earth's crust?*

The mere statement of the facts seems almost enough to convince one of the truth of this theory. But in view of the wide differences of opinion heretofore prevailing we shall examine it in detail, and we believe it will be possible to show that no contradiction can be established, and that it probably is the correct explanation of the mysterious forces which have so long baffled investigators and wrought such havoc in numerous places throughout the world.

It would seem that the obvious fact of the leaky character of the sea bottom, covering three-fourths of the earth, with great internal heat everywhere so close beneath and volcanoes not only abundant on the shores adjacent to the deepest seas, but pouring forth vast quantities of steam when in eruption long ago suggested and apparently ought to have convinced investigators of the validity of this natural and simple explanation. But it appears to have been generally rejected, owing to several circumstances which did not enable investigators to obtain the proper point of view. On the one hand there were traditional theories of volcanoes and their relations to a supposed liquid or molten globe; and on the other little or no adequate knowledge of the enormous number and great violence of submarine earthquakes, which have recently been shown, mainly through the important researches of Professor Milne, to be the most powerful in the deepest oceans.

While volcanoes and earthquakes have been associated from the time of Aristotle and Pliny, and we think justly so, and some mutual connection could hardly be denied; yet even after this relation was especially affirmed by great original investigators like Humboldt and Charles Darwin, it has unfortunately become customary of late years to class earthquakes as volcanic and tectonic or structural. Instead of viewing volcanoes as outlets of pent-up-steam, which blows out if possible the molten rock in which it develops—a clear indication of every great eruption—an effort was made to explain earthquakes as volcanic, with only partial success, whereas both phenomena depend upon the common cause of steam pressure formed deep in the earth's crust, principally by the leakage of waters from the sea. This highly explosive agency is developed so abundantly in the infinitely thin crust between the underlying molten globe, and the overlying oceans, the outcome of a fire beneath and of water above, as in a boiler, that one should not wonder at terrible explosive or eruptive phenomena appearing upon our planet. Considering the vast extent of the oceans it would be strange indeed if something like volcanoes and earthquakes were not inseparably associated with the very nature of the terrestrial spheroid.

If we consider with attention the various causes which might be assigned to explain earthquakes and volcanoes, taking into account their recognized geographical distribution and relation, the relative situation of the inner globe of fire and the overlying layer of water separated from it only by the thin and leaky bottom of the sea, and remembering that both phenomena are augmented to the maximum in regions characterized by high mountains near the deepest oceans, as on the west coast of South and Central America, the Aleutian and Kurile Islands, Japan, Sumatra, Java and other islands of the East Indies, bordering on the deep waters of the Indian Ocean, New Zealand, and the Lesser Antilles in the West Indies, Iceland, Italy, Greece, etc., we shall find the probabilities that steam pressure developing in the earth's crust is the true and common cause both of earthquakes and volcanoes, are as infinity to one against any other conceivable cause, or all other causes combined. The widely extended relationship here pointed out is so intimate and everywhere so confirmatory of the theory that we cannot suppose it to be due to chance.

§ 3. *Views of Professor Milne and his methods of analysis.*

It has been justly remarked by many seismologists that the greatest belt of earthquakes surrounds the Pacific Ocean. Now each part of this great "fire girdle of volcanoes" with innumerable earthquake disturbances has been studied with care by one or more investigators. Without going into the detailed methods of recording and charting developed by Professor Milne, Professor Ewing, Dr. Davidson, Major De Montessus de Ballore, Dr. Agamennone, Dr. Cancani, Dr. Vicentini, Grablowitz, Omori, Koto, Nagaoka, and others, which are of great value for the close study of particular regions, we may call attention to the conclusions of Milne, and Montessus de Ballore regarding the slope of the seashores as important factors in the development of earthquakes.

As a result of careful study of Japanese earthquakes covering eight years, Professor Milne found that "the central portions of Japan where there are a considerable number of active volcanoes are singularly free from earthquakes. The greater number of disturbances originate along the eastern coast of the Empire and many of them have a submarine origin." "Lines 120 geographical miles in extent in running in an easterly or southeasterly direction from the highlands of Japan into the Pacific Ocean, like similar lines drawn from the Andes westwards into the same ocean, have a slope of 1 in 20, or 1 in 30, and in both of these districts earthquakes are frequent. On the contrary, along the faces of flexures which are comparatively gentle, being less than half of these amounts, which may be seen along the borders of most of the continents and islands of the world, earthquakes are comparatively rare. The inference is that where there is the greatest bending it is there that sudden yielding is most frequent."[1]

It seems advisable to quote more at length the full line of thought laid down by Professor Milne in his classic work on "Seismology" (London, 1898). On page 31 Professor Milne says:

"A very much more serious objection to the volcanic origin of the majority of earthquakes is the fact that these disturbances are common in the Himalaya, Switzerland, and other non-volcanic regions. The destructive earthquake in 1891 in Mino and Owari occurred in a region of metamorphic and stratified rocks. Again, an analysis of some ten thousand earthquake observations of Japan shows that there have been but comparatively few which had their origin near to the volcanoes in the country. The greater number of this series originated beneath the ocean or along the seaboard, and as they radiated inland they became more and more feeble, until, on reaching the backbone of the country, which is drilled by numerous volcanic vents, they were almost imperceptible. Beyond this central range of mountains, earthquakes are only rarely experienced, and what is true of Japan seems to be generally true for the coasts of North and South America."

"Throughout the world we find that seismic energy is most marked along the steeper flexures in the earth's crust, in localities where there is evidence of secular movement, and in mountains which are geologically new

[1] Cf. *Seismological Journal of Japan*, 1895, p. xv; and Dutton, "Earthquakes in the Light of the New Seismology," chapter III.

and where we have no reason for supposing that brady-seismic movements have yet ceased.

"As examples of the flexures to which reference is here made, we may take sections running at right angles to the coast lines of the various continents. The unit of distance over which such slopes have been measured is taken at two degrees, or one hundred and twenty geographical miles.

"The following are a few of such slopes:

West Coast, South America, near Aconcagua	1 in 20.2	Seismic districts.
The Kurils from Urup	1 in 22.1	
Japan, east coast of Nipon	1 in 30.4	
Sandwich Islands, northwards	1 in 23.5	
Australia generally	1 in 91	Non-seismic districts.
Scotland from Ben Nevis	1 in 158	
South Norway	1 in 73	
South America, eastwards	1 in 243	

"The conclusion derived from this is that if we find slopes of considerable length extending downwards beneath the ocean steeper than 1 in 35, at such places submarine earthquakes, and their accompanying landslips may be expected. On the summit of these slopes, whether they terminate in a plateau or as a range of mountains, volcanic action is frequent, while the earthquakes originate on the lower portions of the face and base of these declivities. Districts where earthquakes, often followed by submarine disturbances, are most frequent are regions like the northeast portion of Japan and the South American coast between Valparaiso and Iquique. Here we have a double folding. The sea bed, as it approaches the shore line, instead of rising gradually, sinks downward to form a trough parallel to the coast, after which it rises to culminate in mountain ranges. The South American trough which lies within fifty or sixty miles off the coast, like the Tuscarora deep off Japan, attains depths of over four thousand fathoms, and the bottoms of these double folds are well known origins of earthquakes and sea waves."

Professor Milne then goes on to show that where secular movements are active, "the forces which have brought these mighty folds (mountains) into existence have not yet ceased to act." The most important question of all, however, is what are these forces? He says they appear where "mountain formation is geologically of recent origin," and adds:[1]

"The conclusion to which such observations lead is that wherever we find in progress those secular movements which result in the building up of countries or mountain ranges, there we should expect also to find a pronounced seismic activity. Thus, while admitting a few small earthquakes to be volcanic in their origin, we recognize the majority of these disturbances as the result of the sudden fracturing of the rocky crust under the

[1] "Seismology," by John Milne, F.R.S., p. 33.

influence of bending. The after-shocks which so frequently follow large earthquakes announce that the disturbed strata are gradually accommodating themselves to their new position."

Professor Milne's statement that "the greater number of this series (10,000 Japanese earthquakes) originated beneath the ocean or along the seaboard, and as they radiated inward they became more and more feeble, until, on reaching the backbone of the country, which is drilled by numerous volcanic vents, they were almost imperceptible" seems to point directly to the cause set forth in this paper. If earthquakes depend upon the explosive power of steam, they ought not to be numerous near the volcanoes (unless these vents get stopped up), but they ought to be very numerous under the sea in the deep trough just east of Japan, which he says is found to be true by laborious and extensive observations covering a vast number of these phenomena. In order to leave no doubt as to the significance of these results we shall consider also the other lines of thought which he has worked out with so much care.

§ 4. *Inadequacy of the tectonic theory based on slipping and bending, and dislocational and fault movements.*

At present we shall not touch upon all the questions discussed by Professor Milne, but we may remark that slopes of 1 in 20 given above probably are not great enough to produce the least slipping, or fracturing or bending of rocks. The most effectual way to convince ourselves of the truth of this view is by an appeal to the cones of actual volcanoes. Take Mount Cotopaxi, for example. It is one of the tallest active volcanoes in the world, and the most regularly built of all the large volcanoes. The slope is 30°, the angle of the apex being 120°. A slope of 30° corresponds to 1 in 1.732; and thus Professor Milne's ratio of 1 in 20 is less than one-tenth that required to produce stability; and it has escaped his notice that slopes steeper than 1 in 35 are not such that the steepness could give rise to submarine earthquakes and their accompanying landslips. If the cones of volcanoes like Cotopaxi do not slip, when they are more than ten times steeper than the steepest sea slopes, and over twenty times that mentioned as unstable by Professor Milne, why should slips occur under the sea? Obviously the steepness, though no doubt considerable in certain places, is not the cause of earthquakes. Rains, snows and glaciers on Mount Cotopaxi ought to produce slipping of rocks, if anywhere, because the angle is steep and the material loose and unsettled. We are not aware that the slipping of any volcanic cone or other similar mountain has ever been observed to produce a real earthquake; and if slipping were the order of nature, we should expect some enormous slips with corresponding tremors due to this cause near Cotopaxi, Aconcagua, and other great volcanoes (especially when these mountains are shaken at the times of eruption), which are not observed.

We seem compelled therefore to abandon the theory of slipping and bending of rocks[1] except as producing all the time infinitesimal tremors called microseisms, which very likely depend to a considerable extent on this cause. Glaciers are known to be fluid masses, and they move accordingly, though very slowly. It has been shown by the writer (in *Nature*, 1902) that a rock such as marble undergoes secular bending, and is therefore fluid; and we take it that all large rock masses are very similar in their behavior, though their viscosity may be and generally is greater than that of marble; and hence if movement of mountain masses or other large rocks take place, it would seem that, wherever possible, it should be by a very gradual yielding. The cases in which very large masses of rock, like the sides of a mountain, acquire such unstable positions as to fall, do not seem to be very numerous.[2] Accordingly, it is difficult to believe that this cause is very effective in producing earthquakes; for such shocks as might result from it would be rare, small and unimportant. And moreover they could never occur where the average slope is anything like so small as 1 in 20. Besides the arguments here outlined there is another hardly less effective which we shall merely mention, namely: That the forces which may shake an entire continent and send waves of compression and

[1] This hypothesis was originally proposed by Boussingault, from observations made on earthquakes noticed in the Andes remote from known volcanoes, and has at length developed into the tectonic theory now widely held by seismologists and geologists.

[2] The movement by sliding of one or two mountains in the Alps is recorded within the historical period. Among the Andes the most noted change is the collapse of the crater of Carihuairazo, adjacent to Chimborazo, during a violent earthquake on the night of 19–20 of June, 1698. Before this disaster Carihuairazo is said to have been taller than Chimborazo.

distortion through all the rocks between the two oceans, and disturb the whole earth, are not produced by so small a cause as the slipping and bending of ledges of rock.

Humboldt and Charles Darwin long ago associated earthquakes with secular elevations and depressions, and it is noticeable that Professor Milne likewise thinks these disturbances occur with increased frequency in regions where such changes are still in progress.

Montessus de Ballore concluded from his elaborate study of statistical data that in adjacent seismic regions, instability of the earth is increased by differences of topographic relief; and that the unstable regions are associated with the greatest lines of corrugation of the earth's crust. Like Professor Milne, he observes that rapidly deepening shores which slope gently, especially if they are the continuations of flat or moderately falling coast plains, are stable. His results are illustrated by steep regions of the seashore in South America, Japan, and other parts of the world, and by other regions where the slope into the sea is more gradual.

These views and others of similar tenor by several investigators have led some geologists and seismologists to conclude that many of the earthquakes noticed along shores which are steep are due to the sliding of unstable deposits of sediment settling on the rock slopes. But if we recall, as above, the smallness of these slopes, even where the descent is most rapid—it never exceeds that of our mountains upon the land, and is seldom as steep,—and observe that the surrounding sea water is quiescent and would both greatly buoy up and resist the motion of any supposed sliding deposit, so that it is doubtful if appreciable sliding really takes place, and certain that if it does occur the effect in disturbing the earth would be very slight, we shall find it difficult to believe that the theory is well founded. It appears that such a deposit, resisted by the surrounding water, would slide with extreme slowness, and settle gently without any appreciable jar, and consequently no earthquake of importance could be produced in this way.

II. On the Porosity of Matter and on the Leakage of the Ocean Bottoms.

§ 5. *On the porosity and penetrability of matter under the enormous fluid pressure operating in the deepest oceans, and the underlying crust of the earth.*

Somewhat extensive researches on the internal pressures, constitution, and rigidities of the sun and planets, carried out during the past two years and published in the *Astronomische Nachrichten,* have led the writer to the conviction that many of the laws of matter depending on molecular forces, such as impenetrability and solidity, are quite inapplicable to the conditions prevailing in the interior of the earth and other bodies of our solar system; that under the immense pressures there operating, whatever be the temperatures, but especially under the high temperatures known to prevail in the interior of these masses, the hardest natural bodies would yield like sponges, and admit of the most perfect interpenetrability of all the elements. The conclusion was reached from the study of forces of somewhat impressive magnitude that all matter is enormously porous, and quite leaky under forces much smaller even than those operating in the interior of the earth; so that solidity and impenetrability, long held to be among the most universal properties of matter, far from being absolute, appeared to be very relative properties, appropriate to very small, but wholly inappropriate to large, forces, and sometimes set aside by the direct evidence of our senses in common laboratory experiments.

There doubtless are many experiments which would enable us to appreciate the significance of these general principles in specific cases, but it will suffice to recall one close at hand, and directly connected with the question under discussion. In the series of soundings of the depths of the sea carried out some years ago by certain officers of the United States navy occupied with hydrographic and ocean surveys it was found that hollow glass balls with walls several centimetres thick, when subjected to increasing pressure at various depths, came up more and more completely filled with water, in proportion as the depth increased, though no fracture of the glass had occurred, and no holes in it could be discovered by examination of the surface under the highest microscopic power.

After a careful inquiry by many experienced physicists the conclusion was reached that the water had been forced slowly but bodily through the thick walls of the glass under a pressure of less than 1,000 atmospheres, in an interval of less than an hour's time.

In the year 1661 a well-known experiment was made by the Florentine academicians who forced water through the solid walls of a sealed hollow sphere of gold, and other metals, by changing the shape of the sphere under mechanical applications of pressure, so as to diminish the volume. The present case of the porosity of glass was thus verified from the opposite point of view, by the steady application of external fluid pressure, on the spherical surfaces of glass balls sent down in modern soundings of the ocean depths.

The great porosity of all matter has of course long been recognized by physicists, but we are so accustomed to dealing with small forces and the resulting doctrine of the impenetrability of matter that it is doubtful whether our appreciation of this fact has yet passed beyond the academic stage. In his well-known "Properties of Matter," fourth edition, p. 87, Tait says:

> "The porosity of wood, necessary for the circulation of sap, is beautifully shown by the fact that, from microscopic examination of a thin slice of fossil tree, a botanist can tell at once the species to which it belonged. The greater part of the material of the wood has disappeared for it may be millions of years, but its microscopic structure has been preserved by the infiltration of silicious or calcareous materials which, hardening in the pores, have thus preserved a perfect copy of the original. The rapid passage of gases through unglazed pottery, iron and (hot) steel, etc., shows the porosity of these bodies in a very remarkable manner. So does the strange absorption of hydrogen by a mass of palladium. The porosity of steel has recently been shown in a most remarkable manner by Amagat, who forced mercury through a thickness of more than three inches under a presure of at least four thousand atmospheres. The metal was quite impervious to glycerine under the same pressure."

At the time this passage was written, some twenty years ago, Tait remarked that decisive proof of the porosity of vitreous bodies, such as glass, had not yet been obtained, but added "that they form almost a solitary class of exceptions to an otherwise general rule seems highly improbable." He then proceeded to show that all bodies whatsoever must necessarily be porous and leaky when subjected to great fluid pressure, and he pointed out that the penetrability depended greatly on the character of the fluid, thus indicating the great influence of molecular and atomic forces.

To make a practical application of these principles, what shall we now say with respect to the ocean bottoms? In deep places the pressure of the sea water upon them is very great, sufficient to force the water through walls of solid glass several centimeters thick in a short time, and the bed itself in general no tighter than that of a pond in a common field. Obviously, most of these bottoms will leak, and leak at a rapid rate under the enormous pressure operating in the greatest depths of the sea. The bed of the ocean will not leak with equal rapidity in all places, but almost universal leakage will certainly develop; and the water will be driven down into the earth at various rates depending upon the fluid pressure and temperature and the physical character of the sea bottom. Where the rock is volcanic, and badly fractured, or sandy, the leakage will be most rapid, and where the bed is made of fine clay or unbroken granite, the leakage will be much more gradual. It will also depend directly on the depth of the sea, being a maximum where the ocean is deepest, and generally quite insignificant in shallow water. The amount of water leaking through any square meter of the sea bottom will be given by an expression of the form

$$w = P.\, p.\, f(t).\, \phi(T),$$

where P is the fluid pressure in the bed of the sea, and thus directly proportional to the depth; p the average porosity of the ocean bottom, and thus depending on the kind of ooze, dust, sediment and rocks underlying the sea and their state of compression; and $f(t)$ is some function of the time, depending on the average rate of leakage through the successive strata; and $\phi(T)$ is a function of the temperature, and thus increasing with the descent into the rocks of the earth's crust. As water is almost incompressible for small or moderate forces, its escape downward would depend upon the continued descent of that which first entered the bed of the ocean, the rate of which would be diminished under the increasing pressure and density encountered in the lower strata, but on the other hand increased by the rising temperature which makes the rocks more penetrable and also augments their power of absorption. Various values of these quantities, P, p, $f(t)$, $\phi(T)$, would give the several rates of leakage for the corresponding areas of the bottom of the sea. In general it is obvious that the leakage will be most rapid where the sea bottom is fractured or porous, the underlying temperature high, and the depth very great. A rapid rate of leakage would imply that large quantities of water quickly come in contact with the heated rock and develop correspondingly great steam pressure in the crust which underlies that part of the ocean. Tait's remark about the rapid passage of gases through hot steel obviously applies to the absorption and diffusion of steam in hot rock; for this is found by experiment to be quite general for many of the metals. And in the case of lava as it pours from a volcano, it is observed that the molten rock emits vast quantities of vapor, of which, according to Sir Archibald Geikie, 999 parts in 1,000 is steam. This fact in itself is extremely impressive; for it indicates that the remaining thousandth part of the gases emitted, including vapors of sulphur, hydrogen sulphide, hydrochloric and carbonic acid, are derived from the rocks of the earth's crust under the action of steam and the high temperature. We may therefore consider that steam is the only original vapor operating in the crust of the earth.

§ 6. *Daubrée's experiments on the effects of capillarity.*

After this paper was fully outlined and some references were being verified, the author had the good fortune to notice the following significant statement in Sir Archibald Geikie's admirable "Text Book of Geology," fourth edition, 1903, p. 354:

> "An obvious objection to this explanation is the difficulty of conceiving that water should descend at all against the expansive force within. But Daubrée's experiments have shown that, owing to capillarity, water may permeate rocks against a high counter pressure of steam on the further side, and that so long as the water is supplied, whether by minute fissures or through pores of the rocks, it may, under pressure of its own superincumbent column, make its way to highly heated regions. Experience in deep mines rather goes to show that the permeation of water through the pores of the rocks gets feebler as we descend."

In his "Physics of the Earth's Crust," second edition, p. 144, Rev. O. Fisher also makes some interesting remarks on Daubrée's experiments, which are included in his "Rapport sur les progrès de la Géologie expérimentale," Paris, 1867. After describing Daubrée's experiment, Rev. Fisher remarks:

M. Daubrée conceives that if the layer of rock were of great thickness, and a very high temperature maintained in the cavity, a correspondingly high steam pressure would result, which would be sufficient to raise lava in the vent of a volcano, and to produce earthquakes; while the force so obtained might after expenditure be again and again renewed.

"This theory requires the occurrence of cavities at great depth ('supposons une cavité separée des eaux de la surface') communicating with the volcanic vents. But the only argument in favor of cavities existing seems to be that the requisite mechanical force is obtainable by means of them; but it seems *à priori* impossible that there should be such cavities."

These passages are of interest in connection with Part VIII. of this paper, where it is shown that such cavities or partial cavities develop from the expulsion of lava from under the bed of the sea, and the resulting subsidence of the bottom causes the great sea waves which so frequently follow violent earthquakes.

§ 7. *Historical development of the theory of the penetration of sea water.*

Although these passages were found too late to have influenced the theory developed in this paper, they are cited here for convenience, and to show some of the historical aspects of the problem of the penetration of sea water. It was much discussed also in Humboldt's time, as we learn from his remarks in the *Cosmos:*

"The geographical distribution of the volcanoes which have been in a state of activity during historical time, the great number of insular and littoral volcanic mountains, and the occasional, although ephemeral, eruptions in the bottom of the sea, early led to the belief that volcanic activity was connected with the neighborhood of the sea, and was dependent upon it for its continuance."

"For many hundred years," says Justinian, or rather Trogus Pompeius, whom we follow, "Etna and the Eolian islands have been burning, and how could this have continued so long, if the fire had not been fed by the neighboring sea?" In order to explain the necessity of the vicinity of the sea, recourse has been had even in modern times, to the hypothesis of the penetration of sea-water into the foci of volcanic agency, that is to say, into deep-seated terrestrial strata. When I collect together all the facts that may be derived from my own observations and the laborious researches of others, it appears to me that everything in this involved investigation depends upon the questions whether the great quantity of aqueous vapours, which are unquestionably exhaled from volcanoes even when in a state of rest, be derived from sea-water impregnated with salt, or rather, perhaps, with fresh meteoric water; or whether the expansive vapours (which at a depth of nearly 94,000 feet is equal to 2,800 atmospheres) would be able at different depths to counterbalance the hydrostatic pressure of the sea, and thus afford them under certain conditions a free access to the focus."[1]

Again:[2]

"The great number of volcanoes on the islands and on the shores of continents must have early led to the investigation by geologists of the causes of this phenomenon. I have already, in another place (*Cosmos,* Vol. I, p. 242), mentioned the confused theory of Trogus Pompeius under Augustus, who supposed that the sea-water excited the volcanic fire. Chemical and mechanical reasons for this supposed effect of the sea have been adduced to the latest times. The old hypothesis of the sea-water penetrating into the volcanic focus seemed to acquire a firmer foundation at the time of the discovery of the metals of the earth by Davy, but the great discoverer himself soon abandoned the theory to which even Gay-Lussac inclined, in spite of the rare occurrence or total absence of hydrogen gas. Mechanical, or rather dynamical causes, whether sought for in the contraction of the upper crust of the earth and the rising of continents, or in the locally diminished thickness of the inflexible portion of the earth's crust, might, in my opinion, offer a greater appearance of probability. It is not difficult to imagine that at the margins of the up-heaving continents which now form the more or less precipitous littoral boundary visible over the surface of the sea, fissures have been produced by the simultaneous sinking of the adjoining bottom of the sea, through which the communication with the molten interior is promoted. On the ridge of the elevations, far from that area of depression in the oceanic basin, the same occasion for the existence of such vents does not exist. Volcanoes follow the present sea-shores in single, sometimes double, and sometimes even triple parallel rows. These are connected by short chains of mountains, raised on transverse fissures, and forming mountain-nodes. The range nearest to the shore is frequently (but by no means always) the most active, while the more distant, those more in the interior of the country, appear to be extinct or approaching extinction. It is sometimes thought that, in a particular direction in one and the same range of volcanoes, an increase or diminution in the frequency of the eruptions may be perceived, but the phenomena of renewed activity after long intervals of rest render this perception very uncertain."

§ 8. *Views of Lucretius on the penetration of sea water into Ætna.*

We have quote the above passage because of Humboldt's sagacious remarks, some of which deal with the theory of the penetration of sea water as held by the ancients. He mentions Trogus Pompeius under Augustus as the author of the theory, but it is remarkable that the same views were held by the poet Lucretius more than half a century before.

[1] *Cosmos,* Vol. I, p. 242. Bohn's translation.

[2] *Cosmos,* Vol. V, pp. 431–2. All the citations of Humboldt's works are from the Bohn translations.

In "De Rerum Natura," Lib. VI, 680 et seq., we read, according to Munro's translation:

"And now at last I will explain in what ways yon flame roused to fury in a moment blazes forth from the huge furnaces of Ætna. And first the nature of the whole mountain is hollow underneath, underpropped throughout with caverns of basaltic rocks. Furthermore, in all caves are wind and air; for wind is produced when the air has been stirred and put in motion. When this air has been thoroughly heated and raging about has imparted its heat to all the rocks round, wherever it comes in contact with them, and to the earth, and has struck out from them fire burning with swift flames, it rises up and then forces itself out on high, straight through the gorges; and so carries its heat far and scatters far its ashes and rolls on smoke of a thick pitchy blackness and flings out at the same time stones of prodigious weight; leaving no doubt that this is the stormy force of air. Again the sea to a great extent breaks its waves and sucks back its surf at the roots of that mountain. Caverns reach from this sea as far as the deep gorges of the mountain below. Through these you must admit (that air mixed up in water passes; and) the nature of the case compels (this air to enter in from that) open sea and pass right within and then go out in blasts and so lift up flame and throw out stones and raise clouds of sand; for on the summit are craters, as they name them in their own language; what we call gorges and mouths."

In one important part of this passage, the text is corrupt and the context, therefore, supplied; yet there is absolutely no doubt, from preceding passages stating that the sea penetrates the land, that Lucretius held that the mountain is hollow, the water filters through the crevices and cracks in the rocks, until it comes into contact with the subterranean fires which convert it into vapors that give rise to the explosive violence witnessed in the eruptions of Ætna.

We shall see hereafter that Aristotle describes a volcanic eruption as due to the urging blast of pent-up vapor, but it does not seem that he gave any satisfactory explanation of how the vapor developed within the earth's crust.

§ 9. *Lucretius' views on earthquakes.*

"Now mark and learn what the law of earthquakes is. And first of all take for granted that the earth below us as well as above is filled in all parts with windy caverns and bears within its bosom many lakes and many chasms, cliffs and craggy rocks; and you must suppose that many rivers hidden beneath the crust of the earth roll on with violence waves and submerged stones; for the very nature of the case requires it to be throughout like to itself. With such things then attached and placed below, the earth quakes above from the shock of great falling masses, when underneath time has undermined vast caverns; whole mountains indeed fall in, and in an instant from the mighty shock tremblings spread themselves far and wide from that centre. And with good cause, since buildings beside a road tremble throughout when shaken by a waggon of not such very great weight; and they rock no less, where any sharp pebble on the road jolts up the iron tires of the wheels on both sides. Sometimes, too, when an enormous mass of soil through age rolls down from the land into great and extensive pools of water, the earth rocks and sways with the undulation of the water just as a vessel at times cannot rest, until the liquid within has ceased to sway about in unsteady undulations. . . .

"The same great quaking likewise arises from this cause, when on a sudden the wind and some enormous force of air gathering either from without or within the earth have flung themselves into the hollows of the earth, and there chafe at first with much uproar among the great caverns and are carried on with a whirling motion, and when their force afterwards stirred and lashed into fury bursts abroad and at the same moment cleaves the deep earth and opens up a great yawning chasm. This fell out in Syrian Sidon and took place at Ægium in the Peloponnese, two towns which an outbreak of wind of this sort and the ensuing earthquake threw down. And many walled places besides fell down by great commotions on land and many towns sank down engulphed in the sea together with their burghers. And if they do not break out, still the impetuous fury of the air and the fierce violence of the wind spread over the numerous passages of the earth like a shivering-fit and thereby cause a trembling" ("De Rerum Natura," Lib. VI, Munro's translation).

III. The Geographical Distribution of Volcanoes and Their Relation to Earthquake Phenomena.

§ 10. *Four fundamental facts to be explained by a theory of volcanoes.*

A satisfactory theory of the cause of volcanic action must account for the following phenomena:

1. The distribution of some 400 active volcanoes about the margins of the sea, and the numerous eruptions which take place in the sea or on islands, while none at all occur inland at distances exceeding about 100 miles from the ocean or equivalent large bodies of water.

2. The fact that 999 in 1,000 parts of the vapors emitted by volcanoes is steam, as if produced by the leakage of the oceans, near which the volcanic vents always are situated.

3. Volcanoes are particular mountains, and all mountains follow the seashore as if formed in some way by the action of the sea upon the adjacent land.

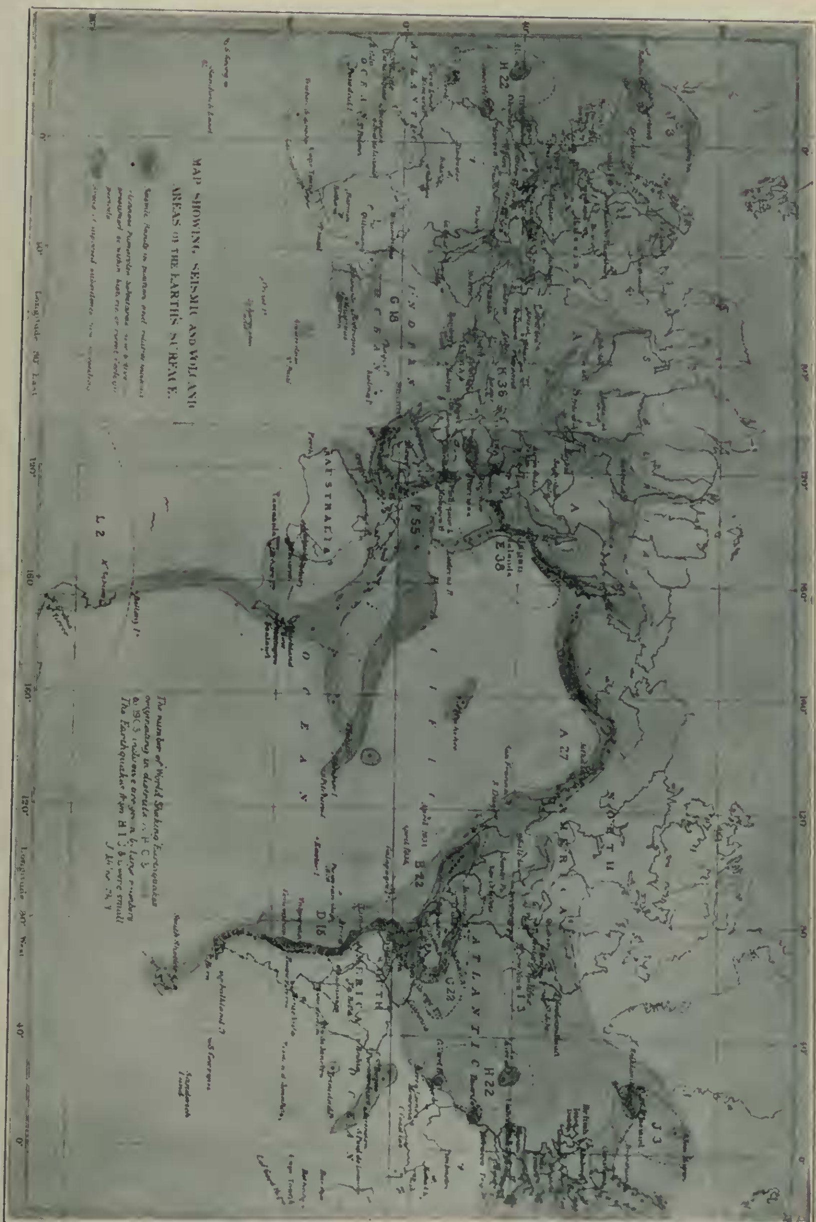

MAP SHOWING SEISMIC AND VOLCANIC
AREAS OF THE EARTH'S SURFACE.

FIG. 2.

4. The close geographical relationship existing between volcanoes and earthquakes throughout the world, and the part played by earthquakes in mountain formation, and the eruption of volcanoes.

These four fundamental facts seem to admit of easy and natural explanation on the hypothesis that the penetration of sea water develops steam just under the crust of the earth, and the result is the upheaval of mountains and the eruption of volcanoes.

§ 11. *Professor Milne's researches on the distribution of earthquakes.*

One of the most remarkable results of recent research is the discovery of numerous regions greatly affected by submarine earthquakes, so that it is now known that these phenomena occur not only on land, but more especially under the sea. As we shall treat of this remarkable result hereafter, we shall at present confine our attention to the relations of earthquakes and volcanoes as observed upon the continents. It has long been recognized that both groups of phenomena occur in a series of belts, which follow the same general regions of the world, along certain so-called lines of weakness in the earth's crust.[1]

In a recent review of earthquakes published in the British Association Report for 1902, Professor John Milne has outlined twelve principal seismic regions, some of them of great extent. These several belts include the wide boundaries of the Pacific Ocean, the Antilles and Caribbean Sea region, and the great belt beginning at the Azores, and extending through the Mediterranean to the Himalayas and India. This last great belt is the only one in which the sea does not predominate over the land, and even here, the sea is paramount over a large part of the area included, while the rest includes or lies adjacent to the highest mountain range in the world. As Major Dutton has remarked, it may be doubted whether all of this last region should be included in one area, except, perhaps, as an outline to aid the memory; but at all events, the Azores and southern

[1] Cf. Professor Milne's work on "Earthquakes," edition 1903, which includes an excellent map of the world giving the distribution of both earthquakes and volcanoes. As earthquakes in the interior of the oceans until recently were seldom recorded, unless of great violence, the earthquakes charted on the map are chiefly those observed on the land, so that the centres of the oceans appear unduly vacant.

Europe, made up throughout of broken mountainous regions extending into the Mediterranean, with the Black Sea and Caspian on the east, are not essentially different from the earthquake regions surrounding the Pacific Ocean.

In his recent Bakerian Lecture at the Royal Society, March 12, 1906, Professor Milne explains his latest classification of seismic regions as follows:

"Regions which lie on the western suboceanic frontier of the American and the eastern frontier of the Asiatic continents, and regions which lie on a band passing from the West Indies through the Mediterranean to the Himalayas.

"In addition to these there are two minor regions, one following the eastern suboceanic frontier of the African continent, which I have called the Malagassy region, and an Antarctic region which lies to the southwest of New Zealand.

"The following table gives the number of large earthquakes or mass displacements which have occurred in the subdivisions of these regions since 1899.

		1899	1900	1901	1902	1903	1904	Total.
Region of the Pacific Ocean.	1. East Indian Archipelago	11	17	13	14	11	9	75
	2. The coast of Japan	19	5	5	9	7	14	59
	3. Alaskan coast	14	11	1	1	3	0	30
	4. Central America	6	4	4	8	6	0	28
	5. West of South America	9	0	2	3	1	0	16
Western Atlantic and Eurasian regions.	6. Antillian region	6	7	3	6	3	0	25
	7. Azores	13	6	3	0	2	1	25
	8. Alpine, Balkan, Caucasian, Himalayan region	4	2	8	22	22	4	62
	9. Malagassy district	9	4	4	1	3	0	21
	10. Antarctic district	Between March, 1902, and November, 1903, 75 large and small disturbances were recorded.						
	Totals	91	56	43	64	58	29	341

"Many of the disturbances included in this table are known to have been followed by hundreds and even thousands of after-shocks. The most active district is at present that of the East Indies, which might well be considered as an eastern prolongation of the Himalayan region. The scene of this activity it may be noticed, is at the junction of two lines of rock folding, which meet almost at right angles. Whether the Antillean and Central American region should be separated is open to question. If we unite their registers as belonging to two comparatively near and parallel earth ridges, the movements of one influencing those of the other, we have a region of hypogenic activity approximate to that of the Japan seas.

"Generally it would appear that these regions of instability are to be found along the margins of continents or tablelands, which rise suddenly to considerable heights above oceanic or other plains.

"At the present time we may, therefore, say that megaseismic disturbances do not occur anywhere, but only in districts with similar contours. Are we dealing with primitive troughs and ridges which are simply altering their dimensions under the continued influence of secular contraction, or do these reliefs of seismic strain represent isostatic adjustments which denudation and sedimentation demand?"

Professor Milne then discusses other possible causes, such as the effects of ocean currents and the seasons, including meteorological causes, such as accumulations of ice and snow at the poles, and finally the motion of the pole in the body of the earth; and he says that in about thirteen years between 1892 and 1904, he "finds records for at least 750 world-shaking earthquakes," which affords one an impressive idea of the extent of his researches, and of the importance of the subject.

In general the geographical distribution of volcanoes is closely similar to that of the earthquakes, but the latter are the more general and widely extended phenomena, while the former are more special. It is remarkable that the volcanoes break out in the centers of the earthquake belts. This relation can not be accidental, but points to a common cause underlying both phenomena.

Besides the active volcanoes near the seashore, and on islands, many of which were heaved up originally by submarine eruptions, nearly every country has a long list of extinct volcanoes. The islands in which volcanic eruptions have ceased, may also be viewed as extinct volcanoes in the sea. In this respect the southern and central Pacific Ocean is particularly rich in extinct volcanoes, and there also, a great many submarine earthquakes are supposed to occur. But the greatest breeding ground for world-shaking earthquakes, as Professor Milne says, are the deep troughs along the continents, near which many volcanoes usually are burning. As volcanic regions, we may mention, especially, the west coast of South and Central America, the Aleutian and Kurile Islands, Japan, the Philippines, Sumatra, Java, and adjacent islands of the East Indies, New Zealand, the region of Erebus and Terror in the Antarctic, and Iceland, the Caribbean Sea, with the Azores and Canaries, the region of the Mediterranean and Central Asia, west of the Himalayas. In such of these regions as fall far within the continents, the volcanoes have in all cases died out for lack of water, but the earthquakes still exist as a survival of former conditions. This is true, for example, in the regions of Central Asia, which no longer has any active volcanoes, though some were active there not very long ago geologically, and thus exhibit still a fresh and even sulphurous appearance.

§ 12. *The outbreak of new volcanoes within the historical period.*

It may be mentioned here that within historical times the following new volcanoes have broken forth:

1. Monte Nuovo, eight miles from Naples, September 28, 1538.
2. Jorullo, in Mexico, September 29, 1759.
3. Izalco, San Salvador, February 23, 1770, 5,000 feet high, thrown up on what was formerly a cattle farm.
4. Las Pilas, on the Plains of Leon, Nicaragua, April 11, 1850, a small volcano.
5. Ilopango, Nicaragua, January 20, 1880, a small volcano, thrown up in a lake 600 feet deep.
6. Fusiyama, Japan, 12,365 feet high, which tradition says was thrown up in a single night, about 300 B. C.
7. Tarewera, New Zealand, January 10, 1886, a mountain with a flat top, which previously had given no volcanic indications.

There are perhaps other volcanoes, some of them mentioned by Strabo, which have broken forth on land; and a good many more which have been upheaved in the sea.

Many old volcanes long extinct have burst forth into renewed activity, generally with terrible violence. Any volcano may become extinct or dormant, and then again break forth. In his work, on "Volcanoes," Professor Bonney often speaks of a mountain as having lost its crater; and mentions in this class Ixtaccihuatl and Chimborazo; but although it is probable, it is not certain that either of these has ever been active.[1] Yet according to the view developed

[1] In his two ascents of Chimborazo, Whymper found lava and other volcanic indications, which had escaped the notice of Humboldt and Boussingault, who did not regard the mountain as volcanic. The adjacent mountain of Carihuairazo, said to have been higher than Chimborazo before the crater collapsed, June 19–20, 1698, might have ejected the volcanic products noticed by Whymper on Chimborazo, though it seems improbable.

in this paper any mountain may become a volcano, on short notice, if the internal violence is sufficient to break open an outlet for the vapors which always slumber beneath. We shall see, hereafter, that the mountains are all filled with volcanic materials, and an explosion is all that is required to set them going, and this is usually effected by the throes of an earthquake. All new volcanoes, and old ones when they burst forth into renewed activity, do so with violent earthquake shocks. The shocks of an earthquake almost always have some effect on a burning volcano, and in earthquakes remote from erupting centers, the breaking out of a volcano causes the shocks to cease, as was long ago noticed by Strabo.

Since this intimate connection has been observed again and again, and the volcanic and earthquake belts are generally similar, though not strictly identical, throughout the world, there is a very strong indication that both depend upon a common cause, and that cause is nothing else than ordinary steam. It is worth while to notice that as Central America is a narrow country, with fairly deep seas on both sides, it is exactly where we should expect volcanic forces to have great sway, and observation shows that this is true for earthquakes as well as volcanoes. The recurrence of frightful earthquakes in that region, and the upheaval of three new volcanoes within historical times speaks for itself, and shows that all the mountains are not yet finished; and that some of the land in Central America is being elevated by forces depending on the influence of the sea, whether volcanic or seismic. As the result of his observations Darwin held that volcanoes break out in rising areas, most likely because an outlet is easily established when the outer layers are cracked open to a great depth.

§ 13. *The relation of earthquakes to volcanoes.*

In his interesting work on "Earthquakes in the Light of the New Seismology," p. 43, Major Dutton follows Professor Milne in his classifications, and remarks:

"Though it is possible to indicate regions which present both volcanoes and earthquakes, there is no proof of interdependence between seismicity and vulcanicity in general. While there are earthquakes which are certainly of volcanic origin, the one phenomenon does not necessarily imply the other."

Professor Milne, Omori, Dutton, and others have recently attempted to disprove the relationship of earthquakes and volcanoes exhibited by the shores of the Pacific Ocean, and their mode of attack has been to show that the volcanoes around the Pacific are not a continuous "girdle of fire," but are bunched here and there, with large spaces between; and that while the earthquakes are also distributed with some irregularity, there is no visible connection between them and the volcanoes.

But if steam forming in the earth's crust from sea water leaking down is the common cause of both earthquakes and volcanoes, should there really be any immediate connection between the two classes of phenomena? Would not volcanoes develop chiefly where the force of the steam was sufficiently powerful and suddenly exerted to break through the crust or mountains, and therefore chiefly in the mountains along the seashore, where the crust is greatly fractured, and enables the violent explosions of steam to blow open an outlet by raising a mountain which would burst into a volcano? It is along such shores also that the leakage would be greatest and most volcanoes should exist, provided the crust becomes badly fractured.

If, on the other hand, the crust is not much broken and explosions of steam cannot break through, would there not result a great many earthquakes of the class now called tectonic because not visibly connected with volcanoes and supposed to be due to slipping of rocks or faults? When the crust is wholly unbroken, it would naturally be very difficult, even for deep-seated forces of enormous magnitude, to raise up a mountain that would become a volcano, because all the overlying strata would have to be violently broken in such a way as to radiate from a point like a star, and ordinarily the strain of the imprisoned steam is much more easily released by an earthquake which merely shakes up the crust in such a way that a neighboring fault moves and the internal pressure is relieved and equalized by scattering, without breaking through all the overlying strata at one time.

This indeed appears to be the process of nature, and if we consider it in relation to volcanoes and earthquakes we shall perceive, in accordance with observation, that the former should be the more special, the latter the more general phenomena. Also both phenomena should occur under the sea, and along the shores of the deepest oceans; but volcanoes would develop chiefly in certain regions where the rocks are already broken in the uplift of mountains and therefore easily burst open, whereas earthquakes might occur in any locality where the leakage of the sea developed sufficient steam. It is undeniable that this is in accordance with observation on our actual earth; and it shows that while both volcanoes and earthquakes should surround the Pacific Ocean, earthquakes are much more widely and uniformly distributed than volcanoes. Also in those regions near actual volcanoes, where the imprisoned steam has a vent, violent earthquakes should not occur; but if the activity of the volcano ceases, the danger of earthquakes would be increased.

Humboldt remarks that this opinion was widely spread among the people of the Andes, and it would be difficult to deny that this result of their long experience was well founded, though confessedly they did not know upon what principle the dreaded explosions depended.

If the leakage from the sea has moderate uniformity with respect to the time, it is clear that the cessation of the smoke of a volcano is really one of nature's danger signals, since the pressure within the subterranean reservoirs of the mountain and adjacent regions may then increase to such a degree as to become extremely dangerous. Neither Krakatoa nor Pelée had been active for long periods before the fearful explosions of 1883 and 1902. Krakatoa had been practically dormant for two hundred years, and while Pelée had experienced an eruption in 1851, it was small, and no important explosion had occurred since 1762.[1] In the case of Vesuvius the general experience is the same—the longer the eruptions are delayed the more violent they become. For it appears that in 79 A. D. no eruption had occurred for about six centuries, and Pliny's description of that outbreak shows that it was more violent than any that has occurred since. The volcano of Conseguina in Central America illustrates the same principle by the long repose preceding the frightful eruption of 1835, which spread devastation far and wide, and in many ways resembled the terrible outbreak of

[1] Cf. Heilprin, "Mont Pelée and the Tragedy of Martinique," pp. 61–187, 188.

Krakatoa.[1] It has so often been observed that the earthquakes ceased on the eruption of a neighboring volcano, that one cannot doubt that direct relief was afforded by the eruption.

Viewing the relation of earthquakes and volcanoes in this light, we can easily understand why many of the so-called tectonic earthquakes are doubly severe—much more violent than those closely connected with volcanoes—because where no volcanic outlet has been available, the explosive strain increases to an enormous extent before it can obtain any relief whatever; and when the yielding does occur the shock is one of appalling violence, and does great damage causing the slipping of rocks, faults and subsidences, and is felt over a very large area, because the explosive strain has become deep-seated and intense.

The great depth at which many of the so-called tectonic earthquakes have been proved to occur, is at once an argument against the dislocational or faulting theory, and a convincing proof that shocks of this type are due to the explosive power of superheated steam. These shocks are obviously too deep-seated to be accounted for by subsidences, and moreover the resulting vibrations are too complex to be due to mere slipping of a ledge of rock, as will be more fully explained hereafter. It may be shown that no possible subsidence of rock faults could produce a conspicuously rotatory earthquake like that which destroyed San Francisco.

IV. The General Cause of the Formation of Mountains and their Geographical Distribution.

§ 14. *On the formation of mountains and cordilleras, as illustrated by the Andes.*

If we consider the deep trough running for a great distance parallel to the coast line of the western shore of South America[2] and recall that other deep troughs of the same kind exist parallel

[1] In chapter XVI of his valuable work on "Earthquakes," edition of 1903, Professor Milne cites several other eruptions of fearful violence accompanied in each case by terrible earthquakes.

[2] The trough is not of uniform depth throughout its course, but the depression is always conspicuous, so that everywhere the earth's crust is arched downward.

to the Aleutian and Kurile Islands, the east shore of Japan, the west shore of Sumatra and Java; also near New Zealand and various islands in the deepest oceans, as Guam, the Bahamas and other West Indian Islands, we shall perceive that this arrangement is not by chance. The South American trough always appears parallel to the great mountain ranges of the Andes, and the fact that it is

FIG. 3.

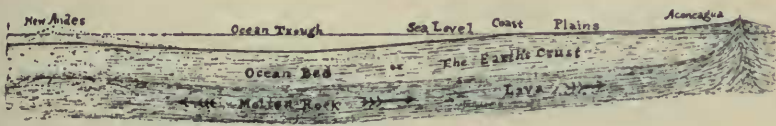
Outline Map of South America, showing the great Ocean Trough parallel to the Andes.

of about the same volume as the matter included in the Cordilleras appeared to be a suspicious circumstance. The relation above cited for Japan, Java, and other islands is similar, but in the case of oval islands the adjacent depression may not be a trough, but rather a hole of somewhat oval or elliptical figure.

Some years ago the writer noticed these remarkable sinks while examining a relief cast of the Atlantic Ocean exhibited in the office of the United States Coast and Geodetic Survey at Washington, and remarked that it seemed as if the volumes of the upraised islands were not very much larger than those of the adjacent depressions. Why should depressions exist so near these elevations above the sea, and, in the case of mountain ranges, so nearly parallel to them for long distances? Is there not obviously a direct connection between the elevated land and the unusual depression in the adjacent sea bottom?

To understand just what this connection is, we may recall that after the great eruption of Mt. Pelée in 1902, it was found by actual measurement that a considerable portion of the adjacent sea bottom

Fig. 4.



Vertical Section perpendicular to the Andes and Andean trough, drawn to natural scale, and showing the mode of operation of the trough in the formation of mountain and cordilleras.

had sunk down hundreds of fathoms.[1] It is impossible to believe that this settling of the bottom of the sea could be due to the

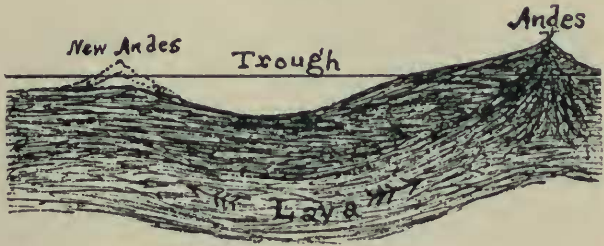
[1]This statement is perhaps somewhat too positive, for Dr. O .H. Tittman, superintendent of the U. S. Coast Survey, informs me that reliable determinations of depth before the eruption of Pelée seems to have been insufficient to decide the question satisfactorily. The cables were broken, and the subject investigated by the French Commission (Lacroix, Alf, La Montagne Pelée et ses éruptions, Paris, 1904), which includes M. Rollet de l'Isle's investigation of the reported changes of depth in the vicinity of Martinique. The French commission was inclined to ascribe the disturbances to submarine volcanic action, rather than to subsidences. This, however, is not a matter of great importance; for in his work on "Seismology," p. 35–36, Professor Milne mentions several well established cases of subsidences in the Mediterranean and in the Pacific Ocean off the Esmeralda River in Ecuador. He points out that "disturbances originating beneath the sea, which are much more numerous than those originating beneath the land, likewise emanate from a region of strain. Mr. W. G. Forster, who has paid so much attention to the earthquakes of the Mediterranean, tells us that they have been accompanied by great subsidences of the sea bottom."

mere shaking of the earthquakes accompanying that eruption; and we must, therefore, suppose that after matter had been expelled by the dreadful explosions which destroyed St. Pierre and devastated Martinique, or in earlier eruptions, a subsidence near the roots of the mountain actually took place. Again, in 1835, Captain Fitzroy and Charles Darwin observed that after the violent earthquake which destroyed Conception, the Chilian coast line in that region had been elevated from three to five feet for several hundred miles. Not only the coast but also the whole country back to the Andes was raised. This could only be explained by the injection or forcing in of a corresponding bulk of lava under the land; and this lava could come from nowhere except from under the bed of the great trough in the adjacent sea. The ultimate effect would be to cause the trough of the ocean to deepen correspondingly. And, moreover, such periodic injections from under the sea trough would not only push along the ejected stream of lava, step by step, until the end of the column reached the mountains, but the forces thus arising would supply the "lateral thrusts" which are said to be much needed for the explanation of the upheavals, the tipping of the strata, the inclinations and sometimes reversed positions of the rocks, and other geological phenomena observed in mountains like the Andes. Heretofore the abundant phenomena of this kind noticed in all high mountains have not been satisfactorily explained. A correct theory must account for the inclinations seen in the mountains as well as the rising of the coast, and such submarine earthquakes as Darwin observed to precede the uplift of the beach at Conception. The present theory seems to be capable of meeting this severe test, and it requires us to make no assumption except that molten lava may be forced from under the bed of the trough, and pushed along its course beneath the crust by the throes of successive earthquakes.

It is recorded that a great sea wave followed the Chilian earthquake of 1835, and such waves are very frequent along the Chilian and Peruvian coasts. They almost always follow an earthquake, and begin by a recession of the sea from the shore, which then returns as a great wave, carrying everything before it. Some have supposed the sea bottom to subside, thus withdrawing the water toward the sink, till it flows in on all sides to fill up the depression, and then piles up and returns as a great wave which continues to oscillate furiously, sometimes for days after the earthquake. We shall consider these waves more fully hereafter, and at present it is sufficient to remark that this explanation is satisfactory for the kind of waves usually observed along the west coast of South America.

We may then suppose that in such earthquakes a very large mass of lava is forced from under the sea, which then settles below its former level, and the great wave follows. If the lava is forced toward the land, the coast or mountains are upraised; if towards the ocean, a ridge may be upheaved there, or possibly a submarine volcano of large extent. In either case the trough of the sea bottom parallel to the coast eventually becomes less stable, and, at certain intervals, settles little by little, when the consistency of underlying

FIG. 5.



lava has been thinned by successive ejections; and thus with the settling stability is again restored.

As the trough is arched downwards towards the exploding lava the steam pressure from beneath cannot force it upward; and the strain is necessarily relieved by motion of the lava towards the Andes or the ocean—usually towards the mountains till the trough gets broad and deep and the mountains very far away and so high that the movement of the column offers unprecedentedly great resistance, when the release will at length become easier towards the ocean by the forcing up of ridges or volcanoes along the other margin of the trough. Ridges with peaks in them will usually result, and this is the beginning of the new Andes or Cordilleras, which are destined to rise slowly from the sea, leaving a deep valley towards the ancient shore, to be drained and filled in by erosion.

Thus we explain some of the remarkable parallel ridges of the Cordilleras. And it is natural that in this upheaval of the crust, release of strain due to subterranean steam pressure should occasionally come by the throwing up of cross ridges, sometimes enclosing undrained areas, and thus lakes like Titicaca are formed. Proceeding upon this simple and natural principle, we may easily explain all the chief characteristics of the Andes. It is impossible to doubt that these mountains have been formed by the very forces which we see still at work there. The upheavals have been step by step, and earthquakes forcing up the mountains have at the same time caused the ejection, by the pushing along of a column or rather a layer, of the necessary matter from under the sea, thus sinking the bottom into a permanent trough, while the subsidences accompanying some of the earthquakes have produced enormous sea waves. Countless thousands and perhaps millions of these earthquakes and sea waves have occurred throughout past geological ages.

The trough parallel to the coast and the upheavals and sea waves now observed are a survival to show us just how the mountains have been formed, and where the next mountain range will form in the sea. We can predict the formation of the new Andes as confidently as we can an eclipse, though it will be a much longer time before the new mountains develop; for we recognize the cause to be a true one, and see just how it works by a kind of self-regulating automatic process. The working of the cause has been observed near Mt. Pelée, and the operation of the same process along the South American coast is proved by the observations of Charles Darwin and by the great sea waves frequently observed within historical times.

§ 15. *Investigation of the significance of the observed lay of mountain chains by means of the theory of probability.*

In their new work on "Geology," Vol. I (p. 543), Chamberlin and Salisbury remark that the relationship between the direction of folded ranges of mountains and the adjacent seacoast is *"a coincidence that is only in part causal."* There are, doubtless, many ways in which this problem could be treated by the methods employed in theory of probability. Without claiming to exhaust the various lines along which the discussion might be developed, we believe the following method rests on equitable considerations.

Imagine a mountain chain like the Andes which runs near the shore cut up into pieces each long enough to reach the sea. If there is no physical cause why the chain should be parallel to the seashore, some of the pieces might be expected to lie at all angles with respect to the shore line of the coast from 0° to 90°, and thus the chain's most probable form is that of a zig-zag line made up of

Fig. 6.

short pieces lying at all angles. Take the intervals of angular distribution of the pieces of the chain at 9°; then, excluding the existence of physical causes, any angle from the first interval, 0° to 9°, to the last of these subdivisions, 81° to 90°, must be held to be equally probable. At any place there are ten divisions of the quadrant, all equally available for the mountain chain to follow. The probability that the direction of a piece of the chain will fall in any one of these divisions of the right angle is one-tenth; and the probability that all the n pieces throughout the whole chain will fall in the same angular division is $(1/10)^n$. When n is a large number, or the chain is long and close to the sea, this probability becomes practically zero. In such a range as the Andes it is observed that all the pieces of the chain do fall in the first division of the angle, between 0° and 9°; and, hence, in general, the probability is $(10)^n : 1$ that the observed lay of the chain so exactly parallel to the shore of the sea is not the result of mere chance, but depends directly on some physical cause which has made the chain essentially straight as well as laid out the general course parallel to the sea coast.

If the chain had the short bends in it here assumed to be possible, the total length would be greater than that of the existing chain, and n would be correspondingly increased. The data used, therefore, make n a minimum, and $P = 1/(10)^n$ a maximum for the given chain everywhere so closely following the seashore. Thus the calculated value of P is too large rather than too small, with the existing lay of the chain.

Another way of reaching analogous results is to consider what the deviation from strict parallelism is in so long a chain, and the probability that the coincidence would be so exact throughout, when all angles between 1″ and 324,000″ (the equivalent of 90°) are equally probable. If no physical cause is involved depending on the sea, there is no reason why the chain should not run at any angle across the shore line. Now, the Andes are made up on the average of at least two parallel chains, and, the probability of this double parallel trend throughout would be only

$$\frac{1}{324{,}000} \cdot \frac{1}{324{,}000} = \frac{1}{114{,}976{,}000{,}000}$$

In any case, we see that for the double chain, the chances are hundreds of billions to one against strict parallelism to the seashore.

In the first method of treatment each part of the chain is considered, without regard to the rest; in the second method, the chain is viewed more as a whole, and the individual parts neglected. In respect to the first method, it might be claimed that as mountains arise from foldings of the crust, and as the earth's crust is thick, a zig-zag form with many bends in it would be improbable, because a crack started in the rocks anywhere would be likely to run in a straight line. There may be some justice in this criticism, but it seems quite fully compensated for by the fact that the chain actually bends wherever the coast line alters its course. Thus in practice the chain is shown to be capable of flexure wherever the shore line changes its direction, and there does not seem anything improbable in many short bends, unless the trend has some connection with the coast. Whether the chain could fairly be conceived as bending at such short intervals is a question we need not enter into, for we may observe that short bends actually appear in certain chains, and thus the hypothesis is not contrary to nature under certain conditions. In the present case we have made no assumption as to causes, except that the lay of the chain is independent of the seacoast, and hence the hypothesis postulates nothing improbable.

To reduce the first method to numbers, we may observe that the length of the chain of the Andes is 4,400 miles and the average distance from the sea about 66 miles. Thus

$$n = \frac{4{,}400}{56} = 66\tfrac{2}{3} \text{ or } P = \frac{1}{(10)^{66}} = 1 : (\text{decillion})^2$$

If other parallel ranges be included, this divisor would be much increased, perhaps nearly squared. On the other hand, the method of viewing the chain as a whole makes the divisor a quantity of the order of one hundred billions. The truth must, I think, lie somewhere between these extremes. If we were to take account also of the mountains parallel to the Atlantic coast, it would certainly be moderate to conclude that the parallelism to the seashore noticed in the whole of South America, so far as it depends on chance, would be less than $1 : (\text{decillion})^2$.

Thus it is clear that the probability of a physical cause connecting the mountains with the parallel shore of the sea is probably more than a decillion decillions to unity, and certainly more than one hundred billions to unity.

The parallelism noticed in North America along the Pacific and Atlantic coasts, is not less pronounced, nor is there less extent of mountains involved. On the contrary, the ranges of North America exceed in length those of South America. The Rocky Mountains are indeed farther from the coast than the Andes, but the shore line has receded since they were formed; while the Sierra Nevada and Coast Ranges are nearer the present shore. When one considers all these circumstances, including the greater length of the chains,

Fig. 7.

and the greater number of parallel ranges, notwithstanding their distance from the seacoast, it will be found that in North America P' is certainly not larger than P as found for South America. Thus we may put them approximately equal to each other, and write

$$P.\ P' = \frac{1}{(10)^{60}} \cdot \frac{1}{(10)^{60}} = 1 : (\text{decillion})^4$$

In Africa the mountain ranges are not high, but they run quite parallel to the shore. We may, therefore, without appreciable error put

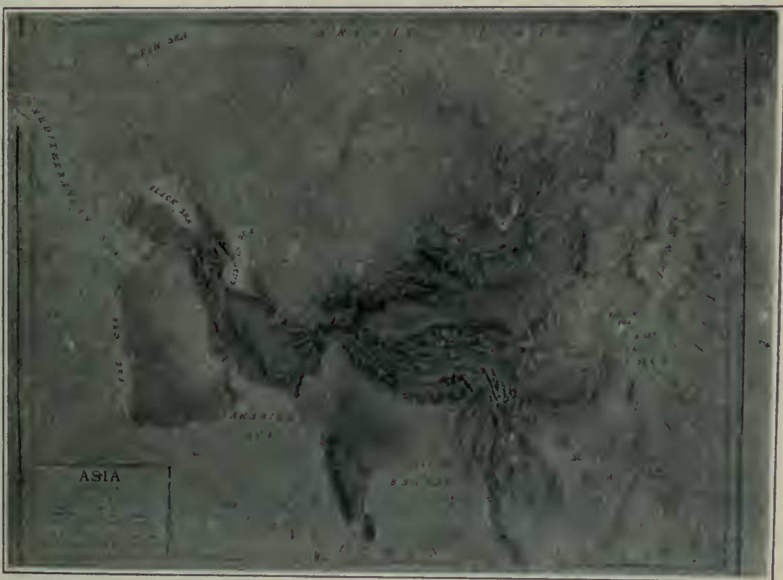
$$P' = \frac{1}{(10)^{66}},$$

and

$$P.\ P'.\ P'' = 1 : (\text{decillion})^6$$

In the other three continents, Europe, Asia, Australia, the lay

Fig. 8.



of the mountains is such as to justify us in taking $P'''.\ P^{\text{iv}}.\ P^{\text{v}} = P.\ P'.\ P''$. And, therefore, for the whole world, we may safely take

$$P.\ P'.\ P''.\ P'''.\ P^{\text{iv}}.\ P^{\text{v}} = 1 : (\text{decillion})^{12}$$

This number is so infinitesimally small, or the divisor is so fabulously large, that it becomes an absolute certainty that the parallelism of the mountains to the seashore depends on a true physical cause, and that cause can be nothing but the action of the sea itself. Since the mountains always *wall in* the land, it follows that they are erected by the sea, through injection of the coast by lava expelled from under the ocean bed. Accordingly, it follows that the crust is bent parallel to the seashore by a true physical cause.

If instead of putting $P = 1 : (\text{decillion})^2$ we had used $P = 1 : (100 \text{ billion})$, the final result would have been $P.\ P'.\ P''.\ P'''.\ P^{iv}.\ P^{v}. = 1 : (100 \text{ billion})^6$.

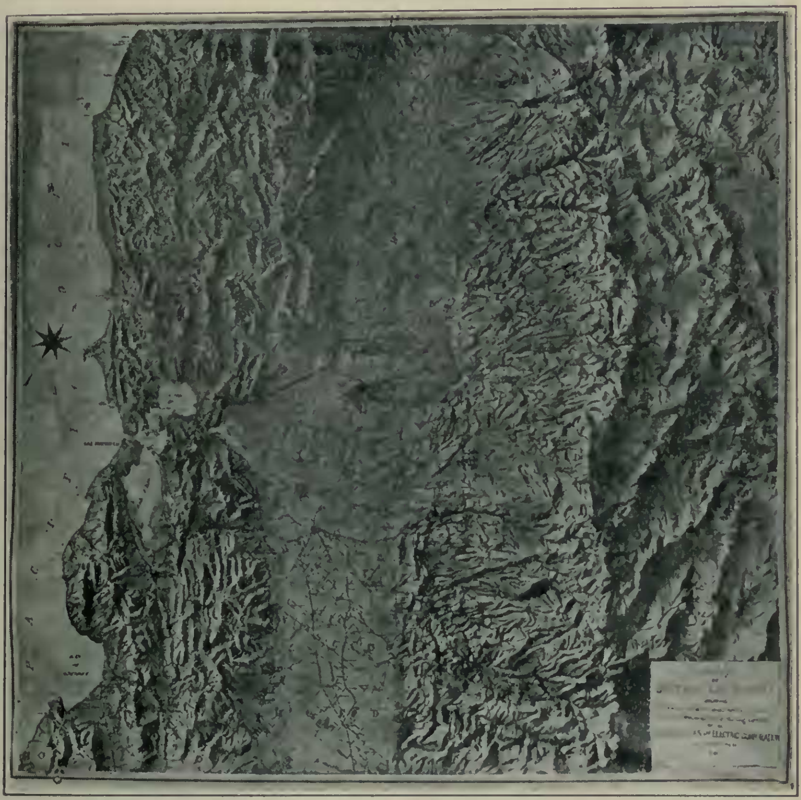
Even this divisor is so infinitely large that the fraction totally disappears, and it becomes an absolute certainty that the lay of the mountains depends on the action of the sea as a physical cause; and that action can be nothing else than the injection of the coast with lava. By this process the mountains were upheaved. The lay of the

FIG. 9.

mountains parallel to the sea is, therefore, no "coincidence that is only in part causal," but the direct outcome of a general law of nature. How universal this law is may be inferred from the unerring precision with which it is exemplified in a region such as that about the Bay of San Francisco. Here the mountains line the shores on all sides, and change their course in such a way as to enclose the bay with walls so close by and well fitting as to leave no doubt about the origin of the surrounding mountains.

A deceptive way of viewing such an argument as the foregoing is to claim that the sea, because of its fluid nature, flows into the depressions in the earth's crust, which are due to subsidence or collapse; and when these depressions are filled up they are bound to be surrounded by higher regions of hills or mountains, due to wrinkles in the crust. This method of reasoning ignores the exact

FIG. 10.



parallelism to the seashore, which held for every mountain chain in the world at the time of its formation, and still holds for nearly all the principal ranges, though in a few cases the lapse of ages has modified the direction of the shore of the adjacent sea.

The result here established is, therefore, a fundamental law of nature, and it gives the key to the leading phenomena of the earth's surface.

§ 16. *How a sea valley develops and gives rise to parallel mountain chains, as illustrated in the San Joaquin, between the Sierra Nevada and Coast Range, in California.*

We have already seen that mountains are raised by the injection of the coast by steam-saturated lava exploding beneath the earth's crust. To understand the entire working of this process under good conditions, we might study the different sea valleys now existing in various parts of the world, or take one which shows the characteristic features of the process. If we could find one in which the process is complete, but of recent date geologically, its present form would, no doubt, enable us to make out the transformation which is undergone at different stages. The Sierra Nevada mountains, with the adjacent San Joaquin valley, appear to be an ideal case to illustrate the process in question.

A study of the Sierras in California shows that the western slopes of these gigantic mountains are very gradual—less than one in fifty—and braced by many spurs, with deep intervening cañons, of which Yosemite is the most famous. The eastern slopes of the Sierras are about ten times steeper than the western, and the jutting spurs are largely wanting. This shows that the injecting forces which raised these mountains came almost entirely from the west; and they continued so long that they finally gave the range an unsymmetrical form[1]—gently sloping and deeply corrugated with cañons on the west, and steep and precipitous on the east.

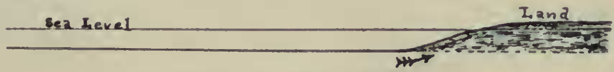
The form thus taken by the Sierras would indicate that at a late stage in their history the San Joaquin valley took the form shown in the accompanying figure, long and sloping on the east and

[1] The more gradual slope of a mountain range toward the sea is due to two causes more or less distinct: (1) The vertical upheaval of the chain, with the successive horizontal thrusts which push it little by little from the sea, thus naturally making the farther slope the steeper; (2) the subsequent elevation of the shore, by injections under the crust, which tips the range still further over, by raising the base of an incline that is already gradual. These two causes combined will be found to explain the principal inequalities in the slopes of mountain ranges as observed in different parts of the world. When the range is being first upheaved, the injections give a nearly vertical uplift; as the range gets older the injections come more and more from the seaward side; when the range itself is finished, the injections only tip its base upward, and make the seaward slope more and more gradual.

steep and precipitous on the west. And when this form was once attained the upheaval of the Coast Range became inevitable. The present position of the San Joaquin river near the western side of the valley still shows this form of the valley, and enables us to see the precise process of transformation.

It is, perhaps, doubtful whether the elevation of these mountains has yet ceased; the earthquakes in California and the low level of the valleys would seem to show that the whole state is still rising,

FIG. 11.



a. Mountain formation just beginning.

b. Mountain formation in the middle stages.

c. Mountain formation in the later stages.

d. New range rising from the sea.

and I am told that this is also shown by beaches and shells at many places along the coast.

The same principles which are here applied to the Californian mountains can be applied to other mountain ranges throughout the world.

§ 17. *Significance of the asymmetry of a mountain chain with respect to its principal axis.*

It is generally noticed that most mountains are unsymmetrical on the two sides; one side has a gradual slope, while the other is steep and precipitous. Moreover, the spurs jutting out from the range are unequally divided between the two sides, the larger number of spurs being on the side where the slope is gradual, which is always turned toward the sea. Let us now examine the meaning of this arrangement. In the new work on Geology by Chamberlin and Salisbury (Vol. I, p. 542–3) we read:

"*Mountain-forming Movements.*—Along certain tracts, usually near the borders of the continents, and at certain times, usually separated by long intervals, the crust was folded into gigantic wrinkles, and these constitute the chief type of mountains, though not the only type. The characteristic force in this folding was lateral thrust. The strata were not only arched, but often closely folded, and sometimes intensely crumpled. In extreme cases, like the Alps, the folds flared out above, giving overturn dips and reverse strata, as illustrated in the chapter on "Structural Geology," pp. 501–511. In these cases there was an upward as well as a horizontal movement, for the folds themselves were lifted; but the more horizontal thrust so much preponderated, and was so much the more remarkable, that the upward movement was overshadowed. It is well to note, however, that these mountain ranges are crumpled *outward* and not *inward,* as might be expected if they resulted simply from the shrinkage of the under side of a thin shell. The folds are sometimes nearly upright and symmetrical, and sometimes inclined and asymmetrical, as illustrated in the chapter referred to. Where the folds lean, the inference has been drawn that the active thrust came from the side of the gentler slope, the folds being pushed over toward the resisting side, and this seems to be commonly true."

Thus we have good authority for the statement that the lateral thrust came from the side of the gentler slope. It is well known that the gentler slope is turned towards the sea, and thus we realize that the forces which pushed the mountains horizontally was directed from the adjacent ocean.

In his great work on "Face of the Earth,"[1] Professor Suess records the following facts, all bearing on the above view:

1. In Vol. I, p. 452, Suess shows that the tangential movement in the Himalayas and Burmese Mountains on the opposite sides of the Bramaputra are in opposite directions, each being directed from the center of the river—exactly what the present theory requires, and not explainable on any other hypothesis.

2. In Vol. II, p. 34, Suess shows that the mountain folds in the eastern part of the United States "have been produced by a tangential movement directed from the existing Atlantic Ocean toward the mainland." On page 139 he shows that the same principle holds for South America.

[1] Oxford Translation by Dr. Hertha Sollas.

3. In Vol. II, p. 121, Suess shows that the "prevailing tangential movement in the Alps and Pyrenees" is toward the north. Thus for the Alps, Lombardy is the most active ancient sea trough; and in the case of the Pyrenees, Suess shows that most of Spain was then in the bed of the sea, and has since arisen (pp. 123–128).

4. That the Sierra Nevada folds were produced by tangential movement from the side of the Pacific is generally recognized by geologists. Dana and others long ago have remarked the same thing about the Andes (Suess, Vol. I, p. 539), and recently, Chamberlin has written me that most of the mountains give evidence of having been upheaved by lateral thrusts from the direction of the sea.

In view of these facts is not the significance of the asymmetry of mountain chains perfectly plain? The unsymmetrical build of the chains shows that the forces by which they were formed were directed from the sea. And, as these forces could not have been subaerial, they must have been subterranean, working just under the earth's crust, and identical with those observed in earthquakes, when lava is expelled from the sea and pushed under the adjacent coast, along which the mountains always run so exactly parallel.

By no possibility could any supposed contraction of the earth have given rise to these features in mountain structure, since in that case it would be impossible for the shape of the ranges and tilting of the strata, pointing to lateral thrust, to be always directed from the sea. The arrangement and structure of mountains thus contradicts the contraction theory of the globe, and shows that any supposed effect of contraction was insensible.

§ 18. *Criticism of the contraction theory of the formation of a range such as the Alps.*

In addition to the considerations advanced by Fisher, as explained elsewhere in this paper, to show that mountains formed by wrinkles in the crust would in no case exceed a very small height, and should, moreover, be distributed with some uniformity over the globe, we may here consider some objections to the view that a chain such as the Alps has been produced by shrinkage.

To get Elie de Beaumont's theory clearly before us, we quote it as given by Lyell, "Principles of Geology," 12th ed., Vol. I, p. 119:

"The origin of these chains depends not on partial volcanic action or a reiteration of ordinary earthquakes, but on the secular refrigeration of the entire planet. For the whole globe, with the exception of a thin envelope, much thinner in proportion than the shell to an egg, is a fused mass, kept fluid by heat, but constantly cooling and contracting its dimensions. The external crust does not gradually collapse and accommodate itself century after century to the shrunken nucleus, subsiding as often as there is a slight failure of support, but it is sustained throughout whole geological periods, so as to become partially separated from the nucleus until at last it gives way suddenly, cracking and falling in along determinate lines of fracture. During such a crisis the rocks are subjected to great lateral pressure, the unyielding ones are crushed, and the pliant strata bent, and are forced to pack themselves more closely into a smaller space, having no longer the same room to spread themselves out horizontally. At the same time, a large portion of the mass is squeezed upwards, because it is in the upward direction only that the excess in size of the envelope, as compared to the contracted nucleus can find relief. This excess produces one or more of those folds or wrinkles in the earth's crust which we call mountain-chains."

It is unnecessary to dwell on the violence of the hypothesis that the nucleus has shrunk away from the crust, as here outlined. So far as one can see, no such result is possible, nor is the shrinkage ever appreciable.

But we may here remark that a radial shrinkage of one mile will give a shrinkage in the semi-circumference amounting to 3.14 miles. Whether correctly or not, it has been estimated by geologists that the amount of folding in the Alps exceeds one-third of the whole space now occupied by these mountains, the shortening of the original crust being placed by Heim at 74 miles. Analogous results have been reached by Claypole and others regarding the mountain ranges of America.

It should be observed that to afford a slack for folds amounting to 74 miles, a radial shrinkage of about 12 miles is required, even when all of the tangential movement is carried round to one point. To carry all the tangential movement round to one point would imply one of two things: (1) That the crust is loose from the globe it surrounds, and thus can be carried around to one point from a whole semi-circumference, which seems altogether improbable; (2) that if the crust is thus shrunk up without being carried around loose from the globe, the matter underlying it must be condensed to about three-halves its former density. The cone of matter underlying the Alps, and extending to the center of the earth would thus have a density 50 per cent. greater than that occurring under neighboring areas. This latter result is impossible, since observations show that the matter under mountains not only is not denser than the average, but actually lighter by an appreciable quantity. We know, therefore, that the wrinkling has not condensed the matter underlying the mountains.

On the other hand, it seems equally incredible that the shrinkage of the whole globe should be brought forward to one point, as if the crust were loose from the globe it covers. No part of the theory of mountains formed by wrinkles of the crust is to be seriously entertained. Besides the difficulties just mentioned, the postulated radial shrinkage of 12 miles is too great. It may well be doubted whether a shrinkage of one mile in the radius has taken place since the continents began to emerge from the oceans.

Professor Suess (Vol. II, p. 552) says:

> "As a result of *tangential thrusts,* the sediment of this (Mediterranean) Sea were folded together and driven upwards as a great mountain range, and the Alps have, therefore, been described as a compressed sea."

We must, therefore, seek the explanation of the formation of the Alps in some process by which this folding can have taken place in the sea, or along its borders, and thus we reach the theory outlined in this paper.

§ 19. *Why we abandon the contraction theory of mountain formation.*

While the considerations here adduced for the origin of mountains seem conclusive, it may not be wholly without interest to point out some difficulties which are not satisfactorily met by the contraction theory, which is the only one now in general use. It is usually stated that mountains result from a crumpling of the earth's crust, and that the crumpling takes place along the principal lines of weakness. This theory fails to explain the origin of isolated peaks or associated groups of peaks which sometimes rise like cones or groups of cones, often more or less intersecting, in the midst of comparatively regular plains. A theory with this serious defect is highly unsatisfactory.

If then the contraction theory fails to explain isolated peaks and groups, which are sometimes pushed up in comparatively level plains, and fails to explain the conspicuous parallelism to the seashores, while the account given of cross ranges and parallel ranges standing in isolation is unsatisfactory, it must be admitted that the theory itself is not well founded.

The assumption that since the continents began to rise from the oceans the earth has shrunk enough to produce great wrinkles in the crust comparable with our high mountains is undeniably a violent hypothesis. For in the writer's paper on the rigidity of the heavenly bodies (*A. N.*, 4104), it is shown that no circulation of currents within the earth has been possible since the globe became encrusted. If there are no currents within, the propagation of heat outward could take place only by conduction; and from Fourier's analytical theory of heat we know that the loss of heat would be extremely slow, and confined almost wholly to a shallow layer near the surface. Indeed it seems probable that the shrinkage of the entire globe is barely comparable to the secular contraction of the cooling crust alone. The approximate accuracy of this view is confirmed by the fact that the crust has not cracked open by pulling apart, as it would do if the crust shrank much more rapidly than the globe as a whole. The fact that the interior of the globe lost very little heat, while the crust cooled all the time, would lead one to think that so far from wrinkling by contraction, the crust ought to have cracked open by the shrinkage of the shell over a nearly unyielding nucleus; but no doubt the process was too slow and the rocks too plastic to give rise to actual rupture of the earth's crust.

Moreover, if the globe shrank, it is inconceivable that this shrinkage could fail to be fairly uniform in the different equal areas of the surface, and thus we should expect the resulting wrinkles to be distributed over the globe with moderate equality and uniformity. Instead of this, we find the mountains, heretofore assumed to be wrinkles, bunched into congested systems, and almost always parallel to the seashore, and larger in proportion to the depth of the adjacent ocean. Is it therefore at all credible that the mountains have really been formed by the shrinkage of the earth? Would it be going too far to say that the whole theory of secular contraction as applied to our encrusted planet is a misconception dating from a time when currents were supposed to circulate freely throughout a liquid globe?

After a careful consideration of the whole question, including all the forces at work, one may well doubt whether the radius of the earth has shrunk a mile since the continents began to emerge from the oceans. The crust could easily accommodate itself to such a small shrinkage as one part in 4,000, without producing any wrinkling whatever.

This subject of planetary wrinkles has been treated mathematically by Professor Sir G. H. Darwin, in his researches on the "Tides of a Viscous Spheroid" (*Phil. Trans. Roy. Soc.*, Part II, 1879, p. 588). And while his results are recognized to be correct, on the hypothesis, they seem to me to be inapplicable to the remote history of the earth, because I believe the shrinkage to have been nearly insensible, and certainly much less effective than has been generally supposed.

In his "Physics of the Earth's Crust," page 118, Rev. O. Fisher has discussed Darwin's theory thus:

"It may be replied to this theory, that the formation of the existing continents cannot be looked at apart from their geological history, and that they are evidently dependent on, and as it were, gathered round, the great mountain ranges in which they culminate. Although these ranges primarily originated long ago in very early geological times, their present loftiness is due to quite late movements; and, if these had not subsequently occurred, they would before now have probably have been razed to the sea-level and have disappeared, so that, whatever cause it was which wrinkled the continents, seems to have continued active to times comparatively, if not quite, recent; and the moon is too far off now. The occurrence of great changes of level at no very distant geological period are manifest from such instances as that related by the elder Darwin."

It has always been extremely difficult to show how contraction could produce elevation of ranges, and the mechanical explanations which have been put forward are admittedly unsatisfactory.[1] The spurs which so often jut out from the main ranges do not look like wrinkles in the crust; for they are too numerous and terminate too suddenly at their extreme ends. The isolated parallel ranges so often met with in Nevada and Southern California also terminate too suddenly to be explained by shrinkage, or by lines of weakness.

In his work on the "Physics of the Earth's Crust," second edition, the Rev. O. Fisher has discussed with much care the inade-

[1] Fisher's "Physics of the Earth's Crust," second edition, p. 123.

quacy of the contraction theory to account for the elevations of mountains actually observed upon the earth. In the case of a solid globe, he finds (p. 122) that the average height of the elevations would be only six and one-third feet. By the theory of probability we easily see that this would absolutely prevent individual elevations, even when exceptionally favored by circumstances, from attaining any considerable height. In the appendix to the second edition, page 58, he examines the mean elevations which will result from the hypothesis of a liquid substratum, and finds that when the radial contraction is 12 miles, "the mean height of all the elevations, due to the corresponding corrugation of the matter above the level owing to secular cooling, is about 44 feet." "It appears," he adds, "therefore as the result of the investigations in this chapter, that the hypothesis of a liquid substratum does not afford such an increased amount of compression as to render it possible to attribute the elevation of mountains to contraction through cooling in that case, any more than in the case of solidity."

When one recalls that our actual mountains are many hundreds and even thousands of times higher than the mean elevations resulting from the contraction theory, it is readily seen how utterly devoid of foundation that theory really is. Considerations adduced in the writer's paper on the rigidity of the heavenly bodies show that the radial contraction of twelve miles used by the Rev. O. Fisher is probably at least twelve times too large; so that the highest admissible mean elevations due to shrinkage would be only a very few feet.

It need scarcely be added that the Rev. O. Fisher must be given the chief credit for showing by long and patient research the inadequacy of this time-honored theory, which was originally suggested by Elie de Beaumont in 1829, and was no doubt a direct outgrowth of Laplace's nebular hypothesis.

We thus seem compelled to abandon the contraction theory entirely, and to explain both peaks and ranges with their striking parallelism to the coast by upheavals occurring near the sea, due to the explosive power of steam, which has heaved up the mountains from beneath. The mountains apparently show this mode of formation, and it explains with equal satisfaction cordilleras and ranges, whether of continued or isolated character, with their numerous jutting spurs and cross ranges, and isolated peaks, which are well-nigh unintelligible on any other hypothesis. And lastly it shows that all mountains are alike inside, whether they burst open and become volcanoes or remain intact.

A theory presenting so many desirable points should have a strong claim to acceptance.

In this connection one geological term in extensive use might perhaps be explained. We refer to the phrase *Line of Weakness* of the earth's crust, which was employed by Leopold von Buch to explain the arrangement of volcanoes along the seashore. It forms wherever the sea stands some time, especially if the sea is deep, because the explosive paroxysms of steam work under the edge of the sea, but not under the land, and, therefore, "lateral thrusts" from the sea begin, while they cease on the land; the result is an injection of the coast line from the direction of the sea, and mountains and volcanoes are upraised, according to the intensity and especially the difference of these forces, from the sea and land, and their duration.

It is not without significance that the height of the mountains are in general proportional to the depth of the adjacent sea, because the forces of injection depend upon the depth, and the elevations produced are proportional to the intensity of these forces. When the sea recedes, however, the extent of the land gained is proportional to the shallowness of the water, and hence arise the large flat plains in many countries. This explains the arrangement of mountains and volcanoes along the sea coast, which has, therefore, been called a line of weakness in the earth's crust. As a matter of fact, any line will prove to be weak where the sea stands for a long time, for mountains and volcanoes will be upheaved there. Thus I conceive that there is originally no such thing as a line of weakness in the crust, and we may with advantage dispense with that unfortunate term. This seems the more advisable, since the earth behaves as a solid, and local weakness developed in the formation of mountains has little effect at a distance, except in volcanic regions or ocean troughs, which act together sometimes throughout their whole extent.

It is shown in the paper on the rigidity of the heavenly bodies that the strength of a planet like the earth is not appreciably dependent upon the crust, but arises primarily from the great pressure acting throughout the body, which itself in turn depends upon the mass and density of the globe. The earth's crust, therefore, has little importance in the theory of the earth, except in our treatment of surface phenomena.

§ 20. *Is there a creeping movement of the fluid substratum beneath the crust?*

The existence of such a powerful seismic zone around the Pacific Ocean, which is surrounded by unfinished mountains and a 'fire girdle of volcanoes' leads one to inquire whether there may not be throughout this vast ocean, as well as in smaller seas, a tendency for the explosive stresses to find relief at the margins, by a slow creeping movement of the particles of the substratum towards the periphery, where the chief relief is afforded. For those stresses arising under the crust in the middle of such an ocean, some relief would be afforded by the rising and sinking of certain oceanic islands; but a greater relief would be afforded around the periphery of the sea, where the great mountain chains are in process of formation. As the crust under the sea is incessantly strained by the heaving of subterranean forces, some parts rising and others sinking, a slow creeping movement of the fluid substratum towards the periphery seems not only possible, but perhaps probable. Such a final movement would be the result of the countless earthquakes which disturb the sea bottom, and in any given earthquake the motion would be extremely slight. The creeping fluid would tend towards the avenues of escape in islands and on the margins of the sea, as well as towards areas still submerged but rising; and thus we recognize forces which under certain conditions may both elevate and depress islands in the sea; but in the long run the sinking tendency will predominate where there is water, and the rising tendency where there is land.

All along the west coast of South America Charles Darwin found conspicuous evidence of elevation within recent geological times; and at Valparaiso the amount was no less than 1,300 feet. The periodic subsidences indicated in certain places by beds of marine fossils of past geological ages, could, I think, be explained by tendencies developed under the crust, according to which the fluid substratum is alternately thickened and thinned, owing to the concurrence or non-concurrence of the subterranean forces. When they work towards a point the result is elevation, and when they tend to diverge from a point the result is depression, and the elevation is transferred to neighboring areas. This is a modern view of the periodic movement of the earth's crust so clearly foreseen by Strabo nearly 2,000 years ago.

According to this view the sea bottoms may oscillate, but on the whole tend to subside, not on account of the shrinkage of the globe, but by virtue of the gradual working out of the underlying fluid substratum, which in the long run pushes up the land.

In his "Principles of Geology," 12th edition, Vol. II, page 155, Lyell discusses with characteristic fairness the historical cases of elevation of coasts noticed in different parts of the world. We shall content ourselves with citing a very few cases of this type:

1. Islands in the sea innumerable, both volcanic and non-volcanic (apparently, though all are raised by volcanic forces).

2. The southwestern end of the Island of Crete, which even Professor Suess admits to have experienced undeniable secular elevation within the historical period.

3. The region about Pozzuoli and the Bay of Naples. This is shown by the famous temple of Jupiter Serapis, and by the elevation of the coast actually witnessed at the time of the eruption of Monte Nuovo in 1538. This raising of the land was confirmed on a larger scale for the whole Bay of Naples during the Vesuvian eruption of April, 1906 (cf. *Quarterly Journal of the Geological Society*, No. 247, 1906), by Professor Lorenzo, who found the elevation of the land at Pozzuoli to be six inches, and at Portici one foot.

4. The foundations of both Ætna and Vesuvius were laid in the sea.

5. Professor Suess cites the most ample evidence of raised beaches and other sea marks high above the present strand in almost all parts of the world. As these heights are very unequal, they cannot be explained by a simple sinking of the sea level, but there must

have been undeniable oscillations of the land, similar to, but on a larger scale, than those observed during the historical period.

6. Conclusive proofs of the upheavals of the Chilian coast during the earthquakes of 1822, 1835, etc., have been given by Lyell, and will not be repeated here. We content ourselves, therefore, with the following account of the Valparaiso earthquake of August 16, 1906, which speaks for itself:

The Great Earthquake at Valparaiso, August 16, 1906.

A special copyrighted cablegram to the San Francisco *Examiner* of August 23, dated Valparaiso, Chili, August 22, says:

"The recent seismic disturbances in this region have thrown up several new islands in Valparaiso Bay. These islands are of various dimensions, some being very extensive while others appear to be mere cone-like rocks jutting above the waters. It is reported that islands have appeared at different points along the coast of Chili. . . .

"The wrenching given the earth's surface is still showing more and more day by day. In sections of the harbor and on the coast, the shore line has been materially changed. Promontories have slid bodily into the sea and in other places strips of coast line have been completely submerged. The theory is that there has been a great uplift of the Andes so as to change almost entirely the contour of the hilly region of the republic. Landslides are everywhere in evidence. Mountain sides have been stripped away and chasms in the hills filled up.

"Persons who have arrived here on horseback from points along the coast say that they witnessed nothing but devastation. Whole villages were wiped out."[1]

[1] Since this paper was finished, Professor H. D. Curtis, in charge of the D. O. Mills Expedition of the Lick Observatory, at Santiago, Chili, has written an interesting letter to Professor Kroeck of the Pacific University at San Jose, which is published in the San Francisco *Argonaut* of November 3. Professor Curtis says:

"A Commission has been appointed to study the shock and its causes. I published a statement that the primary cause was doubtless the same as at San Francisco, the slipping or sliding of one stratum past another, due to the well-known geological fact that the Coast of Chili is very slowly rising. I learn since that the Bay of Valparaiso is now ten feet shallower. So I think the displacement in this shock will prove to be mainly vertical. It may be that the centre of disturbance was under the sea, as Valparaiso suffered much more than Santiago."

Professor George Davidson, President of the Seismological Society of America, informs me that during the great earthquake at Yakutat Bay, near Mt. St. Elias, Alaska, September 3–20, 1899, the land at the head of Yakutat Bay was raised 47⅓ feet. In the Bulletin of the Geological Society of America, vol. 17, May, 1906, will be found a careful investigation by Tarr

§ 21. *Avicenna's views on mountain formation.*

Lyell justly remarks that it is surprising to find among the extant fragments of Avicenna, Arabian physician and astronomer of the tenth century, a treatise on the "Formation and Classification of Minerals," characterized by considerable merit, the second chapter of which is "On the Cause of Mountains." Mountains, according to Avicenna, are formed, some by essential, others by accidental causes. And in illustration of the essential causes, he cites "a violent earthquake, by which land is elevated, and becomes a mountain." In regard to the accidental causes he mentions excavation by water or erosion, which produces cavities, such that adjoining land is made to stand out and form eminences.

The theory of mountain formation adopted in this paper was therefore foreshadowed by Avicenna in the tenth century of our era. It is extremely remarkable that so simple an explanation should have been allowed to slumber for so many centuries, while artificial and highly unsatisfactory hypotheses were in use.

V. Explanation of the Elevation of Particular Mountain Ranges and Plateaus.

§ 22. *On the uplifting of the Andes.*

We have already seen that the Andes have been uplifted by the injection of lava beneath the crust in the earthquakes incident to the heaving of the Andean Valley in the adjacent sea. This has been the chief cause of the original uplift of these great mountains, and the resulting explanation suffices to account for all the principal phenomena. Thus we explain the gentle slope of the mountains

and Martin, who show that the coast was elevated for more than a hundred miles, though slight depressions also occurred in a few places. Elevations of 7 to 20 feet were common, and so little change had occurred in 1905 that Tarr and Martin were able to illustrate their memoir by photographs of the most convincing character. The barnacles and other marine animals were still adhering to the rocks, and there could be no possible doubt about the fact of the elevation. The depression of some areas was made equally clear by the encroachment of the salt water upon forests, which were thus killed. Two of the shocks at this great earthquake (September 10–15) were particularly terrible, the motions recorded in Tokio, 3,300 miles away, being 3/8 and 5/8 inch respectively. Note added December 3, 1906.

on the west and the extreme steepness of the descent on the east;[1] and we also account for the more numerous jutting spurs on the west. On the whole side spurs are much less conspicuous on the east, where descent is more rapid. These characteristics are probably the leading features of the Andes, but there are others deserving of attention, among which we may mention the following:

1. Very great volcanic violence throughout the whole range, and in the peaks of the eastern as well as of the western cordillera.

2. Enormous vertical uplifts, or fault movements, often amounting to thousands of feet, occurring throughout the cordillera, but becoming especially predominant on the eastern side.

3. The vertical uplifting of enormous plateaus such as those of Quito, Caxamarca, Cuzco and Titicaca, the latter being 12,500 feet above the sea.

The heaving of the Andean Valley in the sea seems to be the principal cause of the original elevation of the mountains, but it appears probable that after the mountains were raised to great height another secondary cause contributed to the forces operative in producing the present enormous elevation. This secondary force was nothing else than the soaking tropical rains constantly drenching the eastern slope of the mountains. As the earth's crust was already broken and faulted, the leakage of the water downward would be facilitated, while the ceaseless character of the rainfall would make the eastern slope of the Andes to all essential purposes an inland sea. Effectively, therefore, this great range of mountains is built upon a narrow strip of land with seas on both sides like the mountains in Central America, and hence, the violence of the volcanoes and earthquakes becomes more easily intelligible.

To make this theory more specific we may recall that all the principal peaks about Quito have been volcanic, and three or four volcanoes are still terribly active there now. Just east of Quito, at the head of the Amazon Valley, are the most terrible rainfalls on

[1] Professor Solon I. Bailey, of Harvard Observatory, who crossed the Andes twice, once near Sorata, Bolivia, and again at the Aricoma Pass, and traversed the eastern range a third time through the river Urubamba, writes me that his impression is that the eastern slope is two or three times steeper than the western slope. Few observers have had better opportunities of judging of the general structure of the Central Andes than Professor Bailey.

the earth; and this region is so near to Cotopaxi, Sangay and other active vents as to leave little doubt that it contributes to the activity of the volcanoes. In Whymper's account of his "Travels among the Great Andes of the Equator," p. 240, he cites an interesting passage from the "Royal Commentaries of Peru," p. 632, which runs thus:

"By reason of the continual Rains, and moisture of the Earth, their woolen Clothes and linen being always wet, became rotten, and dropped from their Bodies, so that from the highest to the lowest every Man was naked, and had no other covering than some few Leaves. . . . So great, and so insupportable were the Miseries which *Gonzalo Piçarro* and his Companions endured for want of Food, that the four thousand *Indians* which attended him in this Discovery, perished with Famine. . . . Likewise of the three hundred and forty *Spaniards* which entred on this Discovery, two hundred and ten dyed, besides the fifty which were carried away by *Orellana*. . . . Their Swords they carried without Scabbards, all covered with rust, and they walked barefoot, and their Visages were become so black, dry and withered, that they scarce knew one the other; in which condition they came at length to the Frontiers of *Quitu*, where they kissed the Ground, and returned Thanks to Almighty God, who had delivered them out of so many and so imminent dangers."

In his account of the ascent of Sara-urcu, Whymper says (p. 241):

. . . The scouts came back with bad reports. The animals, they said, could go no farther; there was an end to paths and trails, except occasional wild-beast tracks; there was nothing whatever to eat, and everything must be carried; there was no place to camp upon, the whole country was a dismal swamp; and everlasting rain was falling; so much so that, although they supposed they had been near to Sara-urcu, they were quite unable to be sure. . . ."

Pages 241–242:

". . . This (food) arrived late, and delayed us so much that we could not reach the next camping-place by nightfall, and had to stop in a swamp, on a spot where, if you stood still, you sank up to the knees in slime. This place was just on the divide, nearly 13,000 feet above the sea, and during the greater part of the eleven hours' night sleet or rain fell, rendering it well-nigh impossible to keep up a fire out of the sodden materials. For me the men constructed a sort of floating bed, cutting down reeds, and crossing and recrossing them, piling them up until they no longer sank in the slime. For themselves they made smaller platforms of a similar description, and sat on their heels during the whole night, trying to keep up a fire. . . ."

Page 242:

". . . The land was entirely marshy, even where the slopes were considerable; and upon it there was growing a reedy grass to the height of eight to ten feet, in such dense mass as to be nearly impenetrable. The machetas were found inadequate. It would have taken several weeks' labour of our whole party to have cleared a track over a single mile. The only way of getting through was by continually parting the reeds with the hands (as if swimming), and as they were exceedingly stiff, they sprang back directly we let go, and shut us out of each other's sight. The edges of the leaves cut like razors, and in a short time our hands were streaming with blood, for we were compelled to grasp the stems to prevent ourselves from sinking into the boggy soil. On this day we crossed the divide, and the streams now flowed toward the Atlantic. *The whole country was like a saturated sponge. . . .*"

Page 243:

". . . everything burnable was dripping with moisture, and the surrounding land was so wet that water oozed or even squirted out in jets when it was trodden upon. . . ."

Page 245:

". . . Rain continued without intermission. No one at Cayambe had spoken about these incessant rains. From the aspect of the country (so different from any other part of Ecuador), from the saturation of the hills, the innumerable small pools, streamlets and springs, I am convinced they are nearly perpetual. . . ."

In an excellent account of "A New Peruvian Route to the Plain of the Amazon," published in the *National Geographic Magazine* for August, 1906, Professor Solon I. Bailey, of Harvard College Observatory, describes the route through the Aricoma Pass at an altitude of 16,500 feet, and continues (p. 439):

". . . On reaching the eastern crest of these mountains, if the view is clear, one seems to be standing on the edge of the world. The eye, indeed, can reach but little of the vast panorama, but just at one's feet the earth drops away into apparently endless and almost bottomless valleys. We may call them valleys, but this does not express the idea; they are gorges, deep ravines in whose gloomy depths rage the torrents which fall from the snowy summits of the Andes down toward the plain. We might hunt the world over for a better example of the power of running water. The whole country is on edge. There all the moisture from the wet air, borne by the trade winds across Brazil from the distant Atlantic, is wrung by the mountain barrier and falls in almost continual rain.

"Near the summit of the pass only the lowest and scantiest forms of vegetable life are seen. In a single day, however, even by the slow march of weary mules, in many places literally stepping 'downstairs' from stone to stone, we drop 7,000 feet. Here the forest begins, first in stunted growths, and then, a little lower down, in all the wild luxuriance of the tropics, where moisture never fails. The lower eastern foot-hills of the Andes are more heavily watered and more densely overgrown than the great plain farther down. Here is a land drenched in rain and reeking with mists, where the bright sun is a surprise and a joy in spite of his heat. In these dense forests, with their twisting vines and hanging lianas, a man without a path can force his way with difficulty a mile a day. . . ."

From these accounts, and from the greater steepness of the eastern side of the Andes, I think it clear that the perpetual rain which falls there sinks down as if the country were overlaid by a deep sea, and thus in effect the Andes are on a narrow strip between two oceans. Hence the terrific effects of the volcanic forces, which have not only upraised the peaks and chains, but also plateaus like that of Titacaca. While the western ocean furnished the forces for the original uplift of the chain, the reeking tropical rains must have augmented these forces in the later stages of the Andean development, and this amply accounts for the activity of the volcanoes in the eastern range. These volcanoes might, it is true, be accounted for by the leakage of the ocean, yet it seems probable that the enormous surface rainfall can hardly fail to increase the volcanic violence where the range is already formed, and the rocks broken and tilted to permit of a maximum seepage of the ceaseless tropical rains which constantly soak the eastern side of the mountains.

§ 23. *On the process involved in the elevation of the Alps.*

In the "Face of the Earth," Vol. II, p. 121, Professor Suess shows that "the prevailing tangential movement in the Alps and Pyrenees" is towards the north. Thus we see that the plains of Lombardy and the Valley of the Po constituted the sea valley which was most active in exerting the northern tangential thrusts in folding the Swiss Alps. Professor Suess (Vol. I, p. 274) remarks on the similarity of the Swabian-Franconian sunken area north of the Alps, and the depression of the Adriatic to the south. An examination of almost any good map will convince anyone that the Adriatic once covered the whole of the valley of the Po. The maps given by Reclus in his large work "La Terre," p. 184, show the jutting spurs radiating from the plains of Lombardy into the surrounding mountains on all sides. This result, therefore, is a very happy confirmation of the theory. It is also satisfactory to find that the Pennine range of the Alps, nearest the valley of the Po, including Mt. Blanc, is the highest of these great mountains. The highest range of the Himalayas, including Mt. Everest, also stands nearest the valley of the Ganges; and the process of mountain-formation seems to be such that when several successive ranges are formed and completed that nearest the sea is the highest, probably because the forces there became most nearly vertical.

In Vol. II, p. 552, Professor Suess says: "As a result of *tangential thrusts* the sediment of this (Mediterranean) Sea was folded together and driven upwards as a great mountain range, and the Alps have, therefore, been described as a compressed sea."

From these considerations, it is obvious that the Alps were injected from several sides, but especially from the side of the valley of the Po. In this way, the successive ranges of the Alps were formed, probably beginning near the north, and working southward; and thus we see that the valleys of Switzerland are the results of this successive wrinkling of the crust. Many lakes were formed in the Alps, and these contributed their part to the final shaping of the contours of the country. As the country was surrounded by seas and traversed by many valleys and lakes, all of which gave the water access to the bowels of the earth where breaks of the rocks were once started, the movements finally became very complex, and hence the great difficulty of unraveling the tangled skein of Alpine development. In no other way than this could such a system of mountains have arisen. The average height of the Alpine region is about 4,000 feet, but instead of a level tableland, it is a mass of broken chains and valleys, showing great horizontal crumpling, and also conspicuous and uneven vertical uplifts. The Alps, therefore, afford one of the best illustrations of the theory. For details of the various valleys of the Alps, and the great faults which mark these sunken areas, one may consult Suess, Vol. I, p. 200, et seq.

§24. *On the origin of the Himalayas and of the Plateau of Tibet.*

If we study the general character of the Himalayas by means of the excellent map given in the article, "India," *Encyclopedia Britannica,* ninth edition, we shall find that the most conspicuous feature of this great chain is the prominence of the jutting spurs on the south, facing the ocean. Perhaps a few remarks ought to be made about the process by which these spurs originate.

We have seen that it was by the injection of lava from the sea

Fig. 12.

Map of India.

valleys now occupied by the Ganges and Bramaputra that these mighty mountains were upheaved. In this process there would naturally be certain paths or outlets under the crust, along which the lava would escape most easily; and these outlets would depend upon the upheaval of the overlying strata. A break in the strata perpendicular to the direction of the chain would develop into a spur,[1] because the upheaval would then become easy, and more and more lava would be forced into the outlet thus afforded. By means of the earthquakes accompanying the expulsion of lava from the sea valley the crust is broken at various points, and thus the spurs are gradually developed. It is noticeable in all the great chains that these spurs are directed towards the sea. In the Himalayas, for example, they are on the convex side, while in the Sierra Nevadas they are on the concave side of the chain; which shows that the spurs are not due to any process of shrinkage of the earth. However the chains may curve, the spurs will be found towards the sea valleys from which the expulsions of lava have taken place. This arrangement of the spurs shows the process of mountain formation very clearly.

If we examine the map of Tibet given in the *Encyclopedia Britannica,* ninth edition, we shall find these spurs mainly on the outside of this great tableland. It was therefore injected from the seas on the north as well as on the south; for the Kuen Lun and Altin Tagh mountains on the north show the spurs almost as distinctly as the Himalayas, on the south; and on the north of Tibet the spurs point towards the Arctic ocean. Tibet was thus upheaved by forces injecting this great tableland on all sides. It is thus a very elevated plateau, enclosed by terribly high mountains. Before the upheaval had attained such great height, no doubt the enormous rainfall produced by these mountains, and hence sinking down in the faults thus opened to the bowels of the earth, contributed greatly to the uplifting forces due to the surrounding seas. In this way one may account easily and naturally for the gradual upheaval of the highest plateau in the world.

The forces depending on the valleys of the Ganges and Bramaputra are still active. And the bones of elephants and rhinoceroses now found 15,000 feet above the sea, an elevation at which these animals could not possibly have lived (cf. article "Himalayas," *Ency. Brit.,* by Gen. Strachey), show that the vertical uplift of Tibet took place in comparatively recent geological times. When this tableland had an elevation of a mile or less, it was no doubt inhabited

[1] In §7 we have cited Humboldt's remarks about volcanoes in parallel ranges being connected by cross ranges, forming mountain-nodes. These are similar to spurs, and hence we see why eruptions occur at such points.

Map of Thibet.

Fig. 13.

by numerous large quadrupeds; but after it attained an altitude of two miles they had naturally deserted it; and now, at an altitude of nearly three miles we find only the bones to show that it was once habitable by such animals as now flourish in the low plains of India.

The terrific violence of the earthquakes which are still felt in northern India gives us an idea of the amazing power of the subterranean forces by which this great uplift was produced. In elevating the highest mountains of the world, it is not remarkable that they also raised the highest plateau.

In his work on the "Face of the Earth," Vol. I, p. 452, Professor Suess remarks with surprise that the tangential movement shown by the mountains has *opposite* direction on the two sides of the Bramaputra; this confirms the present theory in the most conclusive manner.

§ 25. *On the elevation of plateaus.*

It will be seen that in this paper we abandon contraction as the principal modifying cause and consider only the light matter proved to be injected under mountains and narrow plateaus by the power of steam, which gives all these masses a substratum of honey-combed material identical with the lighter lava and denser pumice. That this material now lies under these regions of greatest elevation seems certain, and in place of the contraction theory, we may substitute that of steam expansion and solidification, upon which mountain building depends. This is, of course, effected in accordance with Henry's law of gaseous absorption, and the still more general law that matter adapts itself to the pressure to which it is subjected.

It will be seen that all the mathematical reasoning is the same whether we suppose greater contraction under the oceans, or an actual heaving up of the land areas by the injection of light volcanic material more or less full of bubbles, which decreases the average specific gravity of the land and mountains.

Pendulum observations made at many points on land and sea also give the same indication as respects the earth's arrangement of density; and if the present view be sound the interpretation of these observations will now become more obvious.

If we apply the foregoing theory to a narrow plateau, like that of Mexico, which is a uniform tableland, with mountains on both sides, it will become evident that the mountains were formed when they were near the sea; and that when the shore line had remained fixed there for a long time it again receded, after the elevation of the mountains and the tableland, both of which probably were injected with light volcanic materials. Hence the substratum of such a plateau is composed of light materials similar to porous lava and pumice. Only a few mountains, as Orizaba, Popocatapetl, Colima, Jorullo, experienced such violent forces as to come to eruption, but the materials under all of them are the same. The detritus of ashes which the volcanoes eject is nothing but pumice ground to dust by friction and explosive violence. It is obvious that the pumice, ashes and other volcanic materials are not made at the time of ejection, but are always in store, and simply happen to be thrown out of any mountain which experiences eruption. We may in all probability conclude that the plateaus of Tibet, Quito, Caxamarca, Cuzco, Titicaca, and other elevated regions are underlaid by light materials like that thrown from volcanoes. This is certainly true of the great ridges of the Himalayas, Alps, Andes and other mountains which form cordilleras. In fact, the ridges of cordilleras always rest upon a substratum of light volcanic materials, and if they could be exploded from within they would dispense ashes, pumice and scoriæ as abundantly as any volcano. The quantity of this light material forced up under the ridges of mountains depends upon the elevation, and breadth, and is thus enormous in our highest ranges like the Andes and Himalayas. In this way we may explain many of the anomalies of geodesy, and pendulum observations, without any other hypothesis. Is not the accordance of observation with so simple a theory the best proof that the result represents a general law of nature?

§ 26. *On the theory that large segments of the lithosphere act as units and squeeze those segments which lie between.*

In the new work on "Geology" by Chamberlin and Salisbury, which represents the trend of current geological thought, the authors adopt a subdivision of the earth into large segments which are supposed to act as units. The contraction theory is the basis of the reasoning, and part of the discussion is as follows:

"The downward movements are unquestionably the primary ones, and the horizontal ones are secondary and incidental. The fundamental feature is doubtless central condensation actuated by gravity, and the master movements are the sinking of the ocean-basins. The great periodic movements that made mountains and plateaus, and changed the capacity of the ocean-basins, probably started with the sinking of part or all of the ocean-bottoms.

In the greater periodic movements, probably all the basins participated more or less, but some seem to have been more active than others. For example, in the last great mountain-making period, the Pacific basin seems to have been more active than the Atlantic, while in the similar great event at the close of the Paleozoic, the opposite seems to have been true. The squeezing up of the continents doubtless took place simultaneously with the settling of the basins. The true conception is perhaps that the ocean-basins and continental platforms are but the surface forms of great segments of the lithosphere, all of which crowd towards the center, the stronger and heavier segments taking precedence and squeezing the weaker and lighter ones between them. The area of the more depressed or master segments is almost exactly twice that of the protruding or squeezed ones. This estimate includes in the latter about 10,000,000 square miles now covered with shallow water. The volume of the hydrosphere is a little too great for the true basins, and it runs over, covering the borders of the continents. The amount of the overflow fluctuates from time to time, and may be neglected in a study of the movements and deformation of the lithosphere."

Among the major group of squeezed segments we find: (1) Eurasia, (2) Africa, (3) North America, (4) South America; and the minor group includes Australia, Antarctica, the East Indian platform, and Greenland. The depressed or master segments are the oceans: (1) The Pacific, (2) the Indian, (3) the North Atlantic, (4) the South Atlantic; and a minor group of smaller seas, as the Arctic, the Mediterranean, the Caribbean, and the chain of deep pits between the Philippines and the platform of Borneo.

The authors discuss the crowding of these segments towards the center and the crumpling which follows along their edges, accompanied by fracture and slipping.

"If these segments be regarded as the great integers of body-movement, two-thirds of them taking precedence in sinking and the other third in suffering distortion, it is easy to pass to the conception of subsegments, moving somewhat differently from the main segments, so as to aid in their adjustment to one another, and thus to the conception of plateaus and deeps. It is easy also to pass to the conception of mutual crowding and crumpling at the edges of these segments, accompanied by fracture and slipping. These conceptions perhaps represent the true relations between the massive movements of the abysmal and continental segments, as well as the less massive plateau-forming movements and the mountain-forming distortions. The mountains and plateaus are probably the incidental results of the great abysmal and continental readjustments.

"The great movements are probably to be attributed to stresses that gradually accumulated until they overcame the rigidity of the thick massive segments involved, and forced a readjustment. In accumulating these stresses, some local yielding on weak lines and at special points was an inevitable incident in distributing more equably the accumulating stresses. So, also the first great readjustments probably left many local strains and unequal stresses which gradually eased themselves by warpings, minor faultings, etc., so that some minor movements were a natural sequence of the great movements."

From these citations one gets a good idea of the explanations heretofore considered most plausible.

Let us now examine this reasoning a little more closely. Is it mechanically conceivable that large segments of the lithosphere should thus act together as units? Would not such action imply that the the earth is cut deep down into the lithosphere and free to move along the boundaries of these severed segments? If the lithosphere were thus cut up into pieces, and all the segments could be regarded as solid, with abundant lubricating oil between them, they might by their mutual gravity crowd towards the center, and possibly the small ones would be squeezed between the larger. But when we recall that the earth is not cut up in this way, with oil between the pieces, but is one unbroken mass, it is clear that the greatest resistance would arise to relative motion of the parts. The friction of one part against the other would be so amazingly great that no motion would take place at the supposed joint. Even if motion occurred it is impossible to see how the crust could be crumpled without producing a corresponding condensation of the matter underlying the folded area, the density of which would thus be greatly increased, in some cases by 50 per cent. Now geodetic observations show that the density of the matter under the mountains not only is not greater than the average, but actually less; and thus we see that the folds of the crust could not be produced in this way. For in the first place, motion could not take place on account of friction; and in the second place, if it took place, the resulting condensation of the underlying matter would become sensible to geodetic measurement, which is contrary to observation.

Is it not therefore impossible to entertain the doctrine of large segments of the lithosphere moving together and squeezing others between them? Should not this whole theory, along with the hypothesis of contraction in general, be entirely given up?

VI. Confirmation of the Foregoing Theory of Mountain Building by Geodesy.

§ 27. *General considerations on the attraction of mountains.*

If the theory above outlined be admissible it will follow that all mountains are filled with light material like porous lava, which was originally injected as hot lava under great steam pressure, full of bubbles, and is thus similar to dense pumice. When the lava solidified, the bubbles dried up, and left a honeycombed structure of great strength, but comparatively small weight. The deep interior of all large mountains should be filled with material of this kind, which gives strength, but has low density, and the effect of its injection is to reduce the average density of the mountain below that of an equal mass of similar material taken from a plain.

It is remarkable that although some long tunnels through mountain chains have been bored by human effort, none of them has gone more than a mile or so deep, and thus all are too shallow to give us any experimental knowledge of the materials in the depths of the mountains. No large mountain has been eroded to great depth, and hence our only knowledge of the interior of mountains is derived from volcanic action, which blows out the inner portions of some of them. The mountains which happen to break out as volcanoes, either because the subterranean steam pressure is suddenly applied and abnormally great, or because they are weak in some point of their construction, are obviously not different from ordinary chains and peaks, until after they break forth.

Eruptions are always accompanied by violent earthquakes, and a mountain does not take fire and form ashes and cinders by burning, but blows out the volcanic materials already stored up in vast quantities. Thus we naturally infer that all mountains are essentially alike, but we are never able to see the inner contents except of the few of them which have become volcanoes. And if we are able to explore the interior of all mountains, it is only by studying the materials expelled from volcanoes by the explosive power of steam. It is doubtful if even the oldest mountains show erosion a mile deep, and hence we cannot penetrate the earth's crust to any depth except by an analysis of the materials which come out of the mountains after they are blown open in eruption. It is scarcely necessary to add that new ashes, cinders, scoriæ, pumice and other volcanic materials are not as a whole red hot, and therefore the bulk of them is not formed at the time of the first volcanic outbreak. They have been resting quietly under the mountain for immeasurable ages, and one cannot doubt that they exist in all mountains.

It is unfortunate that a custom has arisen of speaking of volcanic action as essentially superficial. While it cannot be said to have any fixed depth, and in many cases may not be extremely deep, it is safe to say that, as a general rule, it is by no means very shallow. On the average the depth is at least of the same order as the height of the mountains, plus the depth of the adjacent sea. There is every reason to suppose the forces which pushed up the Andes and keeps some of them in active eruption arises from about the same depth as the most violent earthquakes which visit that region. Only a few of the peaks of the Andes have become volcanoes, but some of them, as Aconcagua, in Chili, Gualateiri and Sahama, of the Sorata Range in Bolivia, and Cotopaxi and its associates near Quito in Ecuador are all very high; and the ejection of materials at that height requires deep-seated and most tremendous forces. Yet obviously only a small part of the energy originating under the base of a volcano has been spent in ejecting lava, rocks, ashes and cinders; a very large part of the energy exerted from below has been spent in raising the sides of the mountain before eruption broke out at the top.

We may then consider all mountains to be made up internally of light material like that blown out of volcanoes. Chimborazo, for example, may never have had an eruption, and yet it is impossible to believe that its constitution is essentially different from that of the neighboring mountains of Cotopaxi, Pinchinchi, Antisana, Tungurague, Sangay, and Cayambe, all of which are volcanoes.

Now it is a very remarkable fact of observation that geodetic researches in many countries, and pretty much ever since the experiments of Bouguer and La Condamaine on Chimborazo in the year 1738, have tended to show that the matter under the roots of a great mountain is lighter than the average matter of the adjacent plain. In their experiments on the deviation of the plumb line near Chimborazo the existence of great cavities in this colossal trachytic mountain was suspected by Bouguer and La Condamaine, though, as Humboldt remarks, the evidence was unsatisfactory (*Cosmos,* Vol. V, p. 30). Yet the foregoing theory enables us to recognize that the similar widely extended indications of modern geodesy can hardly fail to be real; and according to the principle of continuity the law thus found for certain mountains must be held to be general for all the great peaks and chains of our globe. In fact the satisfactory explanation of this long-standing geodetic problem would seem to be one of the strongest arguments which could be adduced in favor of the truth of the present theory of mountain constitution and formation. For the facts of geodesy are based upon exact observation and experiment, and unbiased by any theory; and yet they become intelligible only when interpreted by means of a general theory like the present. The support thus furnished by a wide body of geodetical facts would seem to place the theory of mountain constitution on a basis where it may become a useful adjunct to the principles of geodetic measurement.

Probably no measurements involving long distances upon the earth have so high an order of accuracy as those of geodesy. Is it too much to hope that the principle of mountain constitution here outlined may become the means of still greater refinement, in the triangulation of the earth's surface?

In his well-known work on the "Figure of the Earth,"[1] Pratt announces a proposition:

"*To deduce from the previous calculations some probable conclusions regarding the constitution of the earth's crust.* The first thing to be observed in the results given in the last paragraph is the very small amount of the resulting deflection at the two extremities of the Indian Arc—Punnæ close to Cape Comorin, and Kaliana the nearest station to the Himalayan Mountains; whereas the effect of the Ocean and Mountains has been shown to be very large. This shows that the effect of variations of density in the crust must be very great, in order to bring about this near compensation. In fact the density of the crust beneath the mountains must be less than that below the plains, and still less than that below the ocean-bed."

Again:[2]

"The circumstance already noticed, that at seven coast stations out of thirteen the deflection is toward the sea, seems to bear testimony to the truth of the theory, that the crust below the ocean must have undergone greater

[1] "Figure of the Earth," 3d edition, p. 134.

[2] *Ibid.*, p. 136.

contraction than other parts. The deflection toward the land at the other six coast-stations can of course easily be understood without at all calling in question the theory. The proximity of the land may easily be conceived sufficient to counteract any effect of the more distant parts of the ocean. It is the fact of even *some* of the deflections being toward the sea, that bears testimony to the theory, while the others offer no argument to the contrary."

"The least, then, that can be gathered from the deflections of these coast-stations is, that they present no obstacle to the theory so remakably suggested by the facts brought to light in India, viz., that mountain-regions and oceans on a large scale have been produced by the contraction of the materials, as the surface of the earth has passed from a fluid state to a condition of solidity—the amount of contraction beneath the mountain-region having been less than that beneath the ordinary surface, and still less than that beneath the ocean-bed, by which process the hollows have been produced into which the ocean has flowed. In fact the testimony of these coast-stations is rather in favour of the theory, as they seem to indicate, by *excess* of attraction towards the sea, that the contraction of the crust beneath the ocean has gone on increasing in some instances still further since the crust became too thick to be influenced by the principles of floatation, and that an additional flow of water into the increasing hollow has increased the amount of attraction upon stations on its shores."[1]

We have quoted this paragraph to recall how geodesists have heretofore attempted to explain the comparative lightness of the matter beneath the mountains, and the greater density of that beneath the plains and especially beneath the sea.

Pratt elsewhere says that the hidden cause of the deflection of the plumb line between the mountain masses on the north and the Indian Ocean on the south "may lie below, in the variations of the density of the earth's crust."[2] He then examines various arrangements of density, and finally calculates by three hypotheses that the sea level in Great Britain stands at a mean height of 1,567 feet higher than it would if the ocean hemisphere with pole in New Zealand became land, other things remaining equal.

§ 28. *Pratt's theorem on the equilibrium of the earth between the land and water hemispheres.*[3]

"There is no doubt that the solid parts of the earth's crust beneath the Pacific Ocean must be denser than in the corresponding parts on the opposite side, otherwise the ocean would flow away to the other parts of the earth. The following reasoning will explain this. Suppose the earth to be a sphere. Through any point on it suppose a surface drawn separating a

[1] "Figure of the Earth," 3d edition, p. 137.

[2] *Ibid.*, p. 148.

[3] *Ibid.*, pp. 159–160.

thin portion on the right hand and through the same point a similar surface separating a like portion on the left. The sphere consists, then, of three parts, the middle portion being of a symmetrical form and attracting the point in the direction of the radius, and the two slender slices attracting it equally to the right and left of that radius. If one of these slices became fluid and of less density than the other, its attraction would be overcome by that of the other, and the fluid would be drawn away to the other parts of the sphere.

"It does not follow that the whole of the fluid would be drawn over. The above process would go in till the surface of the fluid at the circumference of the slice had become so inclined as to be at right angles to the direction of the resultant attraction of the whole mass, solid and fluid. If, however, a narrow channel were cut through this circumference (which would otherwise act as an embankment) the whole of the water would be drawn off.

"Now in the case of the earth there is a channel opening a passage from the New Zealand hemisphere into the opposite one, viz., the North and South Atlantic, and yet the ocean remains in that hemisphere. There must, therefore, be some excess of matter in the solid parts of the earth between the Pacific Ocean and the earth's centre which retains the water in its place. This effect may be produced in an infinite variety of ways; and therefore, without data, it is useless to speculate regarding the arrangement of matter which actually exists in the solid parts below."

Pratt then discusses the original fluidity of the earth, and says finally:

"The conclusion at which we have arrived in Art. 132, that the parts of the crust below the more elevated regions are of less density, and the parts beneath the depressed regions in the oceans are of greater density than the average portions of the surface, seems to bear additional testimony to the fluid theory. For it shows, that notwithstanding the varied surface, seen at present in mountains and oceans, the amount of matter in a vertical prism drawn down at various places to any given spheroidal stratum is the same although its length varies from place to place as the earth's contour varies. No better explanation of this phenomenon can be conceived than that which the fluid hypothesis furnishes; viz., that these prisms though now of different lengths, were, when the crust was fluid, of the same length; and as their lengths are now various simply from the fact that the surface in solidifying has contracted unequally, of course the amount of matter which they contain is the same in all of them."[1]

The views here expressed are very generally recognized by geodesists, and have been treated in different ways by Clarke, Tisserand, Helmert, and other leading authorities.

§ 29. *Results obtained by the United States Coast and Geodetic Survey from recent researches on the average depth of isostatic compensation.*

[1] "Figure of the Earth," 3d edition, p. 162.

With the approval of Dr. O. H. Tittman, superintendent, Mr. J. F. Hayford has recently presented to the Washington Academy of Sciences and published in the *Proceedings* for May 18, a valuable summary of the results deduced from the geodetic operations in the United States. He has discussed with care the long series of deflections of the vertical as determined by Clarke's Standard Spheroid of 1866, which has been found to fit best for the area covered by the United States, and determined the depths at which isostatic compensation takes place. By five solutions of the problem he finds the residuals least for a depth of 71 miles. Some of the conclusions are stated thus:

"The evidence shows clearly and decisively that the assumption of complete isostatic compensation within the depth of 71 miles is a comparatively close approximation to the truth, that the assumption of extreme rigidity is far from the truth—that the United States is not maintained in its position above the sea level by the rigidity of the earth, but is, in the main, buoyed up, floated, upon underlying material of deficient density.

"The conclusions just stated were based upon the 507 residuals considered as one group. The residuals have been examined in separate groups of 25, each group covering a small region. Not a single group of 25 contradicts the conclusion just stated.

"It is certain that for the United States and adjacent regions including oceans, the isostatic compensation is more than two-thirds complete—perhaps much more.

"The departure from perfect compensation may be, in some regions, in the direction of overcompensation rather than undercompensation but in either case the departure from perfect compensation is less than one-third.

"In terms of stresses, it is safe to say that these geodetic observations prove that the actual stresses in and about the United States have been so reduced by isostatic adjustment that they are less than one-tenth as great as they would be if the continent were maintained in its elevated position, and the ocean floor maintained in its depressed position, by the rigidity of the earth."

Mr. Hayford assumed that the compensation is uniformly distributed with respect to the depth, but he remarks that this is only a convenient working hypothesis. Pendulum observations combined with deflection observations, he thinks, may furnish the means of detecting the distribution of compensation. Assuming that the compensation all occurs within a stratum 10 miles thick, the bottom of the stratum of isostatic compensation comes out 37 miles. Mr. Hayford, however, prefers the depth of 71 miles, though he adds that it rests upon an insecure foundation. He concurs with the view now generally held that compensation is always going on, through the changes of levels due to erosion and other causes. Mr. Hayford's paper is extremely important in showing that the depth of compensation is not great, and the principal inequalities of density are essentially limited to the earth's crust, complete average compensation for the whole country occurring within about three or four times that depth. The result, therefore, accords well with the views developed in the present investigation. In his discussion of Hayford's paper, Major Dutton, who was present, remarked that "the heavy masses of sediment which are formed upon the bottom of the sea can, I conceive, only be elevated by a positive uplifting force."

VII. The Origin of Islands and the Secular Movement of the Strand.

§ 30. *Submarine earthquakes and volcanoes.*

The eruption of volcanoes from the sea was noted by the Greeks, as we learn from Aristotle (*Meteor.*, ii, 8, 17–19), quoted by Humboldt in *Cosmos,* Vol. I, p. 240, Bohn's translation:

"The heaving of the earth does not cease till the wind (ἄνεμος) which occasions the shocks has made its escape into the crust of the earth. It is not long ago since this actually happened at Heraclea in Pontus, and a similar event formerly occurred at Hiera, one of the Aeolian Islands. A portion of the earth swelled up, and with loud noise rose into the form of a hill, till the mighty urging blast (πνεῦμα) found an outlet, and ejected sparks and ashes which covered the neighborhood of Lapari, and even extended to several Italian cities."

Strabo (lib. i, p. 59) describes the flaming eruption observed at Methone in the year 282 B. C., near the town in the Bay of Hermione, saying a fiery mountain arose seven stadia in height, inaccessible by day on account of its heat and sulphurous flames, but emitting an agreeable odor at night. It was so hot that the sea boiled for a distance of five stadia, and was turbid and filled with detached masses of rock for full twenty stadia. This eruption is also mentioned by Ovid[1] (Metam., xv).

[1] "Near Troezen is a tumulus, steep and devoid of trees, once a plain, now a mountain. The vapours enclosed in dark caverns in vain seek a passage by which they may escape. The heaving earth, inflated by the force of the compressed vapours, expands like a bladder filled with air, or like a goat skin. The ground has remained thus inflated and the high projecting

Another island eruption on Thera occurred forty-five years later, and the ancients were perhaps familiar with additional submarine outbreaks on the Italian coast; otherwise probably few if any more submarine volcanoes were noted till modern times.[1]

A few submarine volcanoes, either new or of recent origin, were noted by the early navigators, but the phenomenon of volcanic upheavals at sea did not attract much attention till the time of Humboldt, who made a careful study of all such outbursts. In the *Cosmos* Humboldt mentions five submarine volcanoes which appeared in the first half of the nineteenth century. Probably it would be difficult to give a complete list of all the submarine volcanoes which have ever appeared, as the records are widely scattered, and to be of value would have to be critically examined in each case. It is also clear that more such volcanoes would now be noticed than in former centuries, because the travel and exploration of the sea is more extensive than in former ages; yet even now great areas of the ocean are quite seldom visited by ships, so that the world knows little or nothing of what is going on in a large part of the globe. If a submarine volcano of short duration should be upheaved, it might again disappear and leave no record of its existence. Numerous islands are also raised in the sea without visible volcanic outlets. The average number of submarine volcanoes upheaved in a century, if careful watch could be kept on the oceans throughout the world, might prove to be something like one every two years, or 50 in a century. This, however, is merely the number of peaks which would raise their heads above the water. As most of the oceans are much too deep for them to show above the sea level, it is clear that the number which remain covered by the sea is very much greater than those which rise into view, in a ratio of perhaps something like 20 to 1. Thus in the whole earth there may be, and probably are, 1,000 submarine volcanoes erupted in a century, or an average of ten in a year. In this way we may explain some of the great sea waves so often encountered by navigators, and frequently noted by the tide gauges in civilized coun-

eminence has been solidified by time into a naked rock" (Humboldt's, *Cosmos*, Vol. I, p. 239).

[1] The list island chances in the Mediterranean recorded by Pliny in his Natural History is quite impressive (cf. Lib. ii.).

tries. Not all volcanoes thus upheaved would be sufficiently large and energetic in their action to be widely or distinctly felt, because some would be small and slow in their action and hence produce no sensible sea waves. Yet when we consider how much of the sea passes unobserved, and how many sea waves actually are reported, an average of ten submarine volcanoes per year does not seem too high an estimate. Those which are small and in deep water will escape notice entirely; and in midocean none except the powerful eruptions could make themselves felt, because there is no means of detecting a disturbance of sea level, unless it happens to be large enough to disturb a passing ship.

In his well-known article on "Geology" in the *Encyclopedia Britannica,* ninth edition, Sir Archibald Geikie says:

"At the Hawaii Islands, on 25th February, 1877, masses of pumice, during a submarine volcanic explosion, were ejected to the surface, one of which struck the bottom of a boat with considerable violence and then floated. At the same time when we reflect to what a considerable extent the bottom of the great ocean basins is dotted over with volcanic cones, rising often solitary from profound depths, we can understand how large a proportion of the actual eruptions may take place under the sea. The foundations of these volcanic islands doubtless consist of submarine lavas and fragmentary materials, which, in each case, continued to accumulate to a height of two or three miles, until the pile reached the surface of the water and the phenomena became subaerial. The immense abundance and wide diffusion of volcanic detritus over the bottom of the Pacific and Atlantic Oceans, even at distances remote from land, as has been made known by the voyage of the 'Challenger,' may indicate the prevalence and persistence of submarine volcanic action, though at the same time, it must be admitted that an extensive diffusion of volcanic debris from the islands is effected by winds and ocean-currents."

The evidence therefore that the sea bottom is very leaky and in a constant state of eruption in many places seems conclusive. In other places very few eruptions occur, because the underlying rocks are less leaky and the sea is too shallow to exert much pressure. The number of earthquakes under the sea must be much greater than those on land, area for area; but here again few are observed, and still fewer traced to their centers, because the data are insufficient.

It is fully recognized, however, that many submarine earthquakes occur off the east coast of Japan and the Philippines, in the

Aleutian Islands, off the coast of Peru and Chili, near St. Paul's Island in the Atlantic, the Antilles and the East Indies. And while the investigation of these phenomena is still in its infancy, we may be sure they are of wide and universal distribution, especially in the deepest oceans, where the shores are steep and broken, as in volcanic regions. The southern Pacific Ocean, where so many volcanic islands exist, must be a prolific but unexplored center of such disturbances.

§ 31. *Views of Charles Darwin on the distribution of volcanic islands.*

"During my investigations on coral reefs, I had occasion to consult the works of many voyagers, and I was invariably struck with the fact that with rare exceptions, the innumerable islands scattered throughout the Pacific, Indian, and Atlantic Oceans, were composed either of volcanic or of modern coral-rocks. It would be tedious to give a long catalogue of all the volcanic islands, but the exceptions I have found are easily enumerated: In the Atlantic we have St. Paul's Rock, described in this volume, and the Falkland Islands, composed of quartz and clay slate; but these latter islands are of considerable size, and lie not very far from the South American coast: in the Indian Ocean, the Seychelles (situated in a line prolonged from Madagascar) consists of granite and quartz: in the Pacific Ocean, New Caledonia, an island of large size, belongs (as far as is known) to the primary class. New Zealand, which contains much volcanic rock and some active volcanoes, from its size cannot be classed with the small islands, which we are now considering. The presence of a small quantity of non-volcanic rock as of clay slate on three of the Azores, or of the tertiary limestone of Maderia, or of clay-slate at Chatham Island in the Pacific, or of lignite at Kerguelen land, ought not to exclude such islands or achipelagoes, if formed chiefly of erupted matter, from the volcanic class.

"The composition of the numerous islands scattered through the great oceans with such rare exceptions volcanic, is evidently an extension of that law, and the effect of the same causes, whether chemical or mechanical, from which it results, that a vast majority of the valcanoes now in action stand either as islands in the sea, or near its shores. This fact of the oceanic islands being so generally volcanic is also interesting in relation to the nature of the mountain-chains on our continents, which are comparatively seldom volcanic; and yet we are led to suppose that where our continents now stand an ocean once extended. Do volcanic eruptions, we may ask, reach the surface more readily through fissures formed during the first stages of the conversion of the bed of the ocean into a tract of land?"[1]

In connection with the above views of Darwin it should be noted that not all of the islands which are upheaved in the sea could be

[1] "Geological Observations on Volcanic Islands," chapter VI.

expected to pour forth molten rock so as to give above the water a volcanic aspect. In some cases the islands would be raised without eruption breaking out at all, while in others the eruptive outbreaks would occur beneath the sea, and the surface appearance of such islands would be non-volcanic.

§ 32. *Dr. Rudolph's views on submarine earthquakes and eruptions.*

In the first volumes of "Beiträge zur Geophysik" (especially Vols. I and II) Dr. E. Rudolph has several elaborate papers dealing with the subject of submarine earthquakes and eruptions in an exhaustive manner. The large catalogues of such phenomena collected in this careful inquiry are certainly impressive, and the results of Dr. Rudolph's investigations may be said to confirm the view here taken that the sea bottom is in a constant state of volcanic disturbance. These disturbances are in fact so frequent that a similar view is held by many experienced navigators as the result of their own observations. What explanation can be given for such phenomena except the penetration of the sea water into the earth's crust? Volcanic outbreaks never occur except along the shores or under the sea. The significance of these disturbances of the sea bottom and their connection with the formation of islands seems therefore obvious. In the "Face of the Earth," Vol. I, p. 61, Professor Suess remarks on the calm attitude of the scholar in the midst of dangerous natural phenomena, and gives the following interesting account of Apollonius of Tyana:

> "In the year 62 or 65 A. D. Apollonius of Tyana was on the island of Crete. He was on that coast of the island which is washed by the Libyan Sea, on a promontory in the neighborhood of Phästus, and was engaged in conversation with a number of men who had come to do honor to the sanctuary on the promontory, when suddenly an earthquake took place. The roar of the thunder, says Philostratus, did not proceed from the clouds, but came from the depths of the sea, and the sea retired at least seven stadia, so that the crowd were afraid that in its retreat it would carry the temple with it, and wash them all away. Apollonius however said: '*Be comforted; the sea has brought forth new land.*' A few days later they heard that a new island had risen between Thera and Crete."

This account not only illustrates the character of a philosopher, but also shows that even Apollonius recognized that the sea brought forth new land.

§ 33. *On the upbuilding of the smaller areas by gradual upheaval.* We have already studied the process of injection from under the bed of the sea and have seen that the mountains have been upheaved in this way.

This same reasoning is immediately applicable to narrow islands like Japan and Java, with water on both sides. Not only have their mountains been thus upraised, and the volcanoes formed in the backbones of these islands, but the whole tablelands of the islands have been built up in the same way, by the gradual injection of porous lava from under the bed of the sea. If the sea was originally deeper on one side, it has given the backbone of the islands a somewhat unsymmetrical form, the stronger injection and development coming from the deeper sea, but the uplift sometimes makes a wider extent of land towards the shallower water.

This is clearly shown in the formation of numerous peninsulas, as Athos, Longos, Cassandra, Pelion, Attica, Corinth, Argolis, and the three peninsulas of the Peloponnesus in Greece; in Italy as a whole, and especially Calabria and Sicily, the latter being a triangular island with mountains facing the Tyrrhenian, Ionian and Mediterranean Seas; also in Scandinavia and Scotland; in Kamtchatka, Corea and the Malay Peninsula of Asia; and many other places. The same principle is beautifully shown in such islands as Cyprus, Crete, Eubœa and nearly all the islands of the Ægean Sea; in numerous islands along the coast of Dalmatia; in the Æolian Islands, Sardinia, Corsica, Elbe, Ischia and the island of Capri; Minorca, Majorca, Pine Islands, Isle of Wight, and numerous others around Scotland and Ireland. Good illustrations in America are found in the West Indies and the Catalina Islands off the California coast; and in Asia, it is shown beautifully by the form of Saghallien, the islands of Japan, Formosa, Sumatra, Java, and numerous islands in the East Indies; also in New Zealand; and in fact almost universally throughout the world.

In the case of Italy, the Apennines are nearly in the center of the country, but slightly nearer the Adriatic, which was the deeper sea, and did most to elevate the peninsula. The same arrangement is well illustrated in the island of Sicily, where the highest mountains face the deepest seas. All of these and many other obvious illustrations of the principle may be readily found, and must convince even the most sceptical of its general validity.

If we apply this principle to Guam, the Philippines, the Aleutian Islands, Puerto Rico and other islands of the Antilles, we shall be able to explain how the mountains of these countries have been raised, and the islands themselves developed by matter injected from under the troughs near them.[1] This seems to remove all doubt as to the process involved in the formation of islands, and the smaller land areas, and we may consider the plains and slopes of the larger land areas bordering on the sea.

If the injections are powerful, as in South America, the upheaval of matter by the power of steam brings the subsidence of the adjacent bottom and the accompanying sea waves. We need not assume, and we do not assume, any original weakness or line of weakness of the earth's crust, but simply that the ocean bed leaks, and the steam pressure tends to heave it up, and that the process works at various depths from ten to twenty miles, and is continued at irregular intervals over long periods.

This principle of ridges enables us to understand why islands rise from the sea in chains—in such cases they are really submerged and perhaps immature mountains. The Aleutian Islands are now in this state, and many others may be pointed out. When a ridge is once started, the chances greatly favor another parallel to the first, because of the way the sea bottom is depressed nearby, in forcing up the islands from beneath.

If we examine relief maps of the world,[2] we shall see by the mountains parallel to the shores exactly where the ocean used to be and how it gradually withdrew. Thus, the successive ridges of the

[1] As throwing light upon some remarkable processes of stability in nature, it is interesting to notice that when a volcanic cone has been upheaved in the sea, and by successive uplifts raised above the water to become an island, the subsidence that eventually takes place, after much matter has been expelled from beneath the crust to make the island, does not appreciably endanger the island itself, which is powerfully braced by the conical form of its base. When a portion of the sea bottom sinks near by, to partially fill up the cavities in the crust, the settlement of the bed of the ocean scarcely disturbs the island, on account of the way in which the crust is upraised about its base, and braces it on all sides.

[2] Those of Rand, McNally & Co., given in the *Encyclopædia Americana,* have been found extremely useful.

Andes were formed, beginning on the east, and working westward; as the movement progressed the chains got higher and higher, requiring increased volcanic forces; and in the last range, therefore, occur the most and the highest volcanoes. This principle seems to hold not only in the Andes, but generally throughout the world.

§ 34. *On the formation of islands, and on the significance of the symmetrical disposition of their mountains.*

We have already explained the formation of mountains and have seen that they are not due to any shrinkage of the globe with resulting collapse of the crust, but to the injection of lava from the sea, which uplifts the crust into a parallel ridge. The subject of island formation, already alluded to in § 33, has not been much discussed, and it is impossible to say that there is any recognized theory on the subject. When the islands are small they are justly considered mountains in the sea. Some islands are volcanic and are thus volcanoes pushed up in the sea like those occasionally raised on the land. That volcanic islands are similar to ordinary land volcanoes seems clear enough; but how about the larger islands? How did they originate? To answer this question satisfactorily, we may remark that when we look at an ocean like the Pacific and notice how it is dotted all over with peaks projecting above the water, and remember that a still greater number do not reach the surface, we recognize that such peaks were no part of the original constitution of the globe, but have been developed in the sea in the course of immeasurable ages.

Now, as to the larger islands, many of them have conspicuous mountain chains, and the study of the lay of these chains is very instructive. If mountains are wrinkles in the earth's crust, due to the shrinkage of the globe, there is certainly no reason why they should be symmetrically placed on islands. On this theory, the mountains might cross the islands at any angle, or even miss the islands entirely. On actual examination, what do we find to be the fact? When we look at any good map we see the mountains running through the islands with the utmost symmetry, making in all cases a veritable backbone or central axis for the land on both sides. In no cases do the mountains run diagonally or crosswise. To appreciate the significance of this arrangement, look at the map of such islands as Cyprus, Crete, and others in the Mediterranean, Saghallien, Formosa, Sumatra, Java, and others in the East Indies. The regular symmetry of the mountains makes them in all cases the backbones of the islands, and this can only mean that they were formed in their present position by injections from the ocean on both sides; in no other way could such a symmetrical arrangement arise. The universality of this law shows that the mountains depend on the sea, and not at all on the shrinkage of the globe. The same symmetrical arrangement is shown in numerous peninsulas throughout the world.

§ 35. *Why all upheavals do not produce volcanoes.*

It is not necessary for the subterranean forces to break through and form volcanoes—the movement often becomes so deep-seated or feeble with the raising of the mountains that outbreaks do not occur. What takes place in this respect depends on the depth and recession of the sea and the suddenness and violence with which the upheaving pressure is exerted. Thus, along the east coast of South America no large volcanoes were formed, and such small ones as may have once existed have now lost all trace of a volcanic aspect, because the sea was shallow and kept retreating. On the northeast of South America, however, the Lesser Antilles are in deeper water, and when they rise to full growth may form a somewhat imposing chain of mountains, exhibiting volcanic violence depending on the depth of the sea.

In the case of the Alps the development was arrested by the rise of Italy from the Mediterranean, which stopped the sinking of the deep trough which has since become Lombardy. This was formerly the Alpine trough, and it is now so filled up by erosion that the Adriatic is the nearest sea, the recognized recession of which confirms the law.

In the case of the Himalayas also the development was arrested by the rise of the vast plain of India. And while the resulting mountain range became high, volcanic force was at length enfeebled by the shallowness of the troughs where the Indus and the Ganges now flow, and thus it is supposed that no active volcanoes broke forth on the tops of these mighty mountains. If the adjacent water had remained deep, as off the west coast of South America, the Himalayas would doubtless have been broken through by the resulting violence of the volcanic forces. As it was the shallow water, eventually supervening, gave the power for heaving the mountains little by little, and when they attained great height became so feeble or deep-seated that it left them unbroken by volcanic violence. Thus we see why the Alps and the Himalayas, in the main, failed to form volcanoes, and why Africa and Australia are also devoid of these vents (many small ones may have existed and have since lost all trace of this appearance), which chiefly develop near the deep sea, where the sudden exertion of these forces break through the mountain tops. This happens in some cases where the mountains are not very high, either because the seat of the explosion is shallow or the fractures such as to offer but little resistance from greater depth.

In order to break through high mountains, the force has to be extremely powerful, and this is not likely to be the case where the adjacent sea is shallow, as was true south of the Alps and the Himalayas.

Earthquakes in these regions, however, still continue, and have always been abundant, but they are deep-seated, owing largely to the filling in of the Alpine and Himalayan troughs, and lead to no eruptions, and hence have been called tectonic. They are clearly a survival, due to the same forces which upheaved the mountains, but the sea having so far receded they cannot blow open any cones at this late date. In fact the centers of disturbances usually are somewhat remote from the mountains at present and diffused over such an area in the ancient trough that their power for rupture is slight.

§ 36. *Gradual secular desiccation of the oceans indicated by the lowering of the strand lines throughout the world.*

The raising and lowering of the land by subterranean forces which have effected the withdrawal and encroachment of the sea over the land was first advocated by the Greek geographer Strabo, who adopted the theory of Archimedes that the figure of the ocean surface is that of a sphere (cf. Suess, "Face of the Earth," Vol. II, p. 2). This theory has been much developed in modern times and explains numerous movements of the strand line. But according to the elaborate study of this question made by Professor Suess, the elevation and subsidence theory even in the oscillatory form adopted by Lyell, is inadequate to account for the general lowering of the strand line noticed throughout the world. After his careful study of this question, Professor Suess is unable to adopt any satisfactory explanation of the observed phenomenon, and the whole problem remains an enigma to the investigator of the physics of the earth. An impartial examination of all the arguments leads me to believe that the conceptions of Strabo, as developed into the oscillatory theory advocated by Lyell, is adequate to account for many more of the phenomena of the earth's surface than Professor Suess concedes; yet it seems not only possible, but even probable, that an additional cause is at work which must contribute somewhat to the general lowering of the strand line throughout the world. This additional cause is nothing else than the secular desiccation of the oceans, brought about mainly by the sinking of the waters into the crust of the earth, where the resulting steam becomes the motive power in earthquakes.[1] A certain amount of water is also taken up as water of crystallization in the development of crystalline rocks, which extend somewhat deeper from age to age.

The view of earthquakes here adopted makes sea water the principal disturbing cause. Of the water which thus sinks below the crust, an appreciable part, but by no means all of it is expelled by volcanic action; and thus there is a steady accumulation of water deep down in the earth's crust. If this view be well founded, there is thus a secular desiccation of the waters of the globe, depending on the penetration of water to the deeper parts of the crust, and also on the absorption of water by rocks in crystallization and otherwise. How rapidly this process goes on cannot be accurately known at present; but on the basis of data observed within the historical period, we may reasonably hold that the fall of the strand line due to this cause is on the average less than a meter in 2,000 years, and most likely of the order of one-tenth of this amount.

The desiccation here postulated seems to be a *vera causa,* and this process, in connection with the oscillatory movement of the land recognized by Lyell and other geologists as necessary for the

[1] The sinking of the sea bottom when lava is expelled from under it also increases the capacity of the ocean basins, and thus slightly lowers the strand line.

explanation of such phenomena as the coal measures, gives us a simple and natural way of explaining leading phenomena of the strand. We have elsewhere explained why the movements of faults must be attributed primarily to the formation of steam-saturated lava at the depths whence earthquakes originate.

The steam which induces this movement naturally remains hidden in the earth, and as the process goes on uninterruptedly from one geological age to another, there is a gradual secular desiccation of the waters of the sea, and a correspondingly slow lowering of the strand line.

To determine the average rate of this lowering of the strand we would have to take a figure somewhat smaller than that found in the different countries since a given geological epoch, and even then, the result would be partly vitiated by the effects of secular elevation of the land. In any case, the movement depending on secular desiccation of the oceans is extremely slow.

This view that there is a secular desiccation of the waters of the sea is not new, but was entertained in different forms by Benoist de Maillet (1692), Celsius (1743), Von Hoff (1822), Goethe and others (cf. Suess, "Face of the Earth," Vol. II, Ch. I).

Professor Suess' exhaustive discussion of the movements of the strand line will be found chiefly in chapters XII–XIV of Volume II of the "Face of the Earth." He considers the lowering of the sea level to the extent of hundreds of meters within recent geological time to be proved. The cause here suggested gives the only explanation of the phenomenon which seems at all probable or consistent with known facts.

§ 37. *On the gentle movements of the land.*

In many parts of the world, the rocks are comparatively unbroken, and leakage is very slow and gradual. This may correspond to the beds of shallow seas or to the land when level and unbroken by mountains. In all such regions the water which may seep down would give rise to a very evenly diffused subterranean steam pressure and the chances are that any movement which might take place would prove to be very slow and gradual. The strain being nearly equalized at all points, there would be no heaving required to adjust the nearly even balance of the forces, and consequently earthquakes of sensible strength would seldom or never occur. In this way we may explain the comparative immunity of many districts from earthquakes.

Yet, when an even pressure thus arises, it may produce a steady elevation of the land. Bending and warping of the strata may also occur where the stresses are steadily applied, and under the circumstances the rocks would probably change their figure slowly without snapping; when the earthquakes are more violent the rocks are broken into smaller pieces and fault movements increase.

§ 38. *Oscillations of the strand shown in such phenomena as the coal measures and fossil beds.*

No special effort is made in this paper to explain all the phenomena of the earth's crust which offer difficulty to the geologist; and hence we have been chiefly concerned with phenomena of elevation. But ever since the time of Aristotle and Strabo it has been justly remarked by sagacious observers that there has been not only elevation of the land, but under certain conditions also subsidence. Lyell and many other writers have discussed these oscillatory movements which are well exhibited by the successive layers seen in many of the coal measures. Some of these layers may be explained by the effects of damming up and drifting of vegetation to places where it did not grow; but even when allowance is made for these causes, there still seems ample evidence of an oscillatory movement of the land in many places. This is also well shown in fossil beds, where sea shells often alternate with brackish water species.

The expansion and contraction of the limits of the sea over large areas of the low-lying shore is a frequent phenomenon, and a slow oscillation of the strand seems the only rational explanation of it yet offered. Such an oscillation is most easily explained by a substratum of fluid beneath the earth's crust, such as we show to exist. Under just what conditions the land sinks is not clear. The instability may result from a number of causes of which the most probable would seem to be: upward movement of neighboring regions, thus weakening the support of the region in question and perhaps putting additional load upon it, while the underlying fluid layer slowly yields, thus causing subsidence. If during an earthquake a neighboring area should be started upward, the strain would naturally equalize itself in that direction, and the movement might continue for a long time until subterranean conditions changed. The earth's crust is complex, of unequal thickness in different parts, and broken into unequal blocks by various faults, which are continually adjusting themselves to the strains arising in the underlying substratum supporting them. That some areas should go up while others go down is therefore not at all remarkable; and most of the oscillations of the land will be found to depend upon causes of this kind. In my opinion the seat of the forces will be found to lie mainly in the fluid substratum beneath. Considering the great number of blocks into which the earth's crust has been shown to be broken by faults such as Professor Suess has so fully discussed for the regions of the Alps and the Tyrol, the oscillations of level with the changes of the strand in salt and fresh water regions seem easily accounted for.

In his work on "Meteorics" (lib. I, cap. 12) Aristotle justly remarks:

"The distribution of land and sea in particular regions does not endure throughout all time, but it becomes sea in those parts where it was land, and again it becomes land where it was sea. . . .

"And the sea also continually deserts some lands and invades others. The same tracts, therefore, of the Earth are not, some always sea, and others always continents, but everything changes in the course of time."[1]

§ 39. *Strabo's views on the elevation and depression of the land.*

In his "Principles of Geology" (pp. 24–25, 12th edition) Lyell quotes the views of Strabo regarding the elevation and depression of the land as follows:

"It is not," says Strabo, "because the lands covered by seas were originally at different altitudes, that the waters have risen, or subsided, or receded from some parts and inundated others. But the reason is, that the same land is sometimes raised up and sometimes depressed, and the sea also is simultaneously raised and depressed, so that it either overflows or returns into its own place again. We must, therefore, ascribe the cause to the ground, either to that ground which is under the sea, or to that which becomes flooded by it, but rather to that which lies beneath the sea, for this is more movable and, on account of its humidity, can be altered with great celerity. It is proper to derive our explanations from things which are obvious, and in some measure of daily occurrence, such as deluges, earthquakes and volcanic eruptions, and sudden swellings of the land beneath the sea; for the last raise up the sea also; and when the land subsides again, they occasion the sea to be let down. And it is not merely the small, but the

[1] Cf. Lyell's "Principles of Geology," 12th edition, Vol. I, pp. 21–22.

large islands also, and not merely the islands, but the continents which can be lifted up together with the sea; and both large and small tracts may subside, for habitations and cities, like Bure, Bizona, and many others, have been engulfed by earthquakes."

VIII. On the Great Sea Waves which frequently accompany Violent Earthquakes.

§ 40. *Great sea waves caused chiefly by the subsidence of the sea bottom after the lava has been expelled by the throes of earthquakes.*

We have already shown how the sea bottom may subside over a large area after a violent earthquake which has forced out from beneath the bed a large amount of steam-saturated lava. This lava is usually forced up under adjacent mountain ranges, mountain peaks and volcanoes, or under the intervening coast plains. If relief is afforded by forcing the column of molten matter along so that the remotest part raises in the mountains, which are at the top of the arched portion of the neighboring region of crust, we should have no means of discovering the resulting slight elevation of the peaks. For the heights of mountains are always uncertain by several feet, because extremely exact levels are difficult to establish so far above the sea. We are thus unable to say whether the various peaks and ranges are rising in height, or to tell what fluctuation of altitude they may undergo from time to time, by the heaving of earthquakes. In the case of plains near the sea it is easier to detect changes of level, but in many places characterized by violent earthquakes unfortunately no such observations are taken. Tidal observatories are best adapted to keeping record of any changes of level that may occur, because it is only by analyzing the tides carefully that we can detect changes of the sea level.

As already remarked, the sudden upheaval noticed in the seacoast of Chili after certain earthquakes was especially remarked by Charles Darwin and Capt. Fitzroy, who experienced the severe earthquake at Conception, February 20, 1835, and noticed the resulting elevations of the coast line.

Let us consider briefly the upheavals of the Chilian coast witnessed by Darwin and Fitzroy. The only reasonable explanation of this fact is that lava had been forced under the coast, and it is obvious that the matter must have been expelled from under the bed of the sea. We do not know whether the lava was injected as a thin layer or the whole body of the material under the coast slightly pushed back to afford relief of the strain under the sea, but a displacement of the latter kind seems the more probable. A sea wave of considerable magnitude[1] was noticed on that occasion, but it was not so large as sometimes develops, and the sea bottom may have subsided only very slightly. But on August 13, 1868, the whole South American coast from Valdivia in Chili to Guayaquil in Ecuador was violently shaken by a terrible earthquake, with its highest intensity near Arica. A few minutes after the earthquake the observers were surprised and alarmed to notice the sea slowly receding from the land, and very soon vessels which had been anchored in seven fathoms of water were left high and dry, with no means of escape. In a short time their surprise was converted into terror at the sight of a mighty ocean wave fifty or sixty feet high returning with terrible velocity and carrying everything before it. The vessels stranded on the beach at Arica, including the U. S. S. *Wateree,* were swept up by the gigantic wave and carried nearly a half mile inland and again left stranded higher than before.[2] The wave rolled back and after a short interval again swept the shore; and the furious oscillation of the water thus started continued for a day or two before the sea finally quieted down. This great sea wave was propagated over the Pacific and observed almost all over the world.

In 1877, May 9, another great earthquake visited the same region and was followed by a wave of even greater magnitude, of exactly the same type, the water first slowly receding from the land, and then returning as a gigantic wave carrying everything before it. This wave of 1877 is known as the Iquique wave. At Arica the hulk of the stranded U. S. S. *Wateree* was again picked up and carried still further inland, which would indicate that at Arica the height of this wave surpassed that of 1868. The sea continued to oscillate in periods of something like an hour and did not subside for a couple of days.

[1] In his valuable work on "Earthquakes," chapter IX, Professor Milne gives a catalogue of sea waves. Different waves present different phenomena, and we here treat only of the best established types.

[2] Dutton, "Earthquakes in the Light of the New Seismology," p. 281.

These two are good types of those great sea waves in which the water recedes from the land in the first few minutes following the earthquake.

Major Dutton and others have suggested that the sea bottom sinks, and the explanation we have given of how this takes place seems satisfactory and free from objections. It is clear that if by the throes of the earthquake a large body of lava is forced from under the bed of the Andean trough, the bed might thereupon settle from twenty to fifty feet over a large area.[1] The great inrush of the water following this subsidence would withdraw it from the land, and as soon as the rushing currents met in the center of the trough, they would raise the water into a high ridge, and its subsidence would give the first great wave which rolled in upon the devastated shore. With the first depression of the water over the ridge, another inrush would take place, again withdrawing the sea from the shore, and another great wave would follow like the first, but of slightly feebler intensity. And so the oscillations of the sea would continue for a day or two, till they became reduced by friction to insensible magnitude. This explanation accords with all the known facts, and the recognized laws of fluid motion. Assuming it to be correct, the result is of interest as showing the effect of friction in destroying the motion of the sea, which has often been discussed in connection with the problem of the tides. In this case, the length of the wave of 1868 has been calculated to be about 100 geographical miles; and as the depth of the sea is between four and five miles, we see that the wave length involved is from twenty to twenty-five times the depth of the sea.

At the close of this section we shall give another possible explanation of waves of this kind, which begins with a recession of the water from the shore; but meanwhile we shall notice waves of a different class, sometimes encountered, which begin by a sudden rising of the water near shore.

The great wave which overwhelmed Simoda, Japan, December 29, 1854, may be taken as a type of those which are characterized by the sudden inrush of a great wave without any previous recession

[1] The subsidence might be much greater if the area affected was proportionally diminished.

of the sea near the shore. At 9:15 a. m. Vice Admiral Putiatin on board the Russian frigate *Diana* noted very powerful shocks of an earthquake, and a little before ten o'clock a huge wave was seen coming which quickly overflowed the city. Major Dutton remarks that the time here involved, and the known speed of propagation of such a wave, indicates that it originated over 100 miles from the shore, in the Tuscarora trough, where the depth attained is over 4,000 fathoms.

If it originated so far away, it might have resulted from the sinking of the sea bottom, as in the Arica and Iquique waves, the withdrawal of the sea when the waters rush into the sink becoming so nearly insensible at the great distance of Simoda as to escape notice in the bay. But a more probable explanation is that the sea bottom just east of the Tuscarora deep was heaved up into a ridge with elevation of 20, 30, or 50 feet. This would produce the great wave which so suddenly appeared to overwhelm the city. In this case there would be no preliminary recession of the water whatever, and the wave would come without the least warning, as appears to have been the case.

In case the wave originated by a subsidence of the bottom of that trough, a slight withdrawal of the water from shore should have been noticed even at that great distance; but if the upheaval occurred beyond the trough, the greater inrush of water from that side may have obscured the slight recession which otherwise might be expected at Simoda. The upheaval is conceivable in the manner we have described, either with or without subsidence of the bed, and ordinarily the disturbance might be on either side of the trough; but in this case the time shows that the uplift probably was beyond the trough.

§ 41. *Another explanation of sea waves on the hypothesis of submarine eruptions.*

The only other rational way of explaining these great sea waves is by means of the uprush following the explosion of a submarine volcano. We consider his explanation much less satisfactory than that already given, but it is undeniable that in certain cases it might account for both classes of sea waves, especially where the water is deep and we can suppose the volcano to be upheaved near shore and of large size.

Let the accompanying figure illustrate a section perpendicular to the shore of the sea and land, on a coast like that of Chili or Peru, where this phenomenon has so often been observed in a typical way, and the water is deep.

Suppose a volcano to be formed at some distance, say 50 or 100 kilometers from the shore. If a great wave is produced we may assume the volcano to be raised to a height of 1,000 or 2,000 meters, or even higher; but as the sea is seven or eight kilometers deep, this will only reach one-seventh or, at most, one-fourth of the way to the surface. In the throes of the earthquake the volcano is raised, and the water forced up immediately over the eruptive center; and the steam, stones, lava, dust and ashes are driven upward towards the surface, as in the explosion of a land volcano. The explosion is

FIG. 14.

Submarine volcano.

resisted by the great depth of the water, which is hurled upward in a violent current from the orifice. The steam condenses to water by the low temperature of the ocean, and the other gases are absorbed, whether coming from the bed of the sea or formed in the water by the intense heat of the red hot lava. The current of steam and flying stones, lava, sand and ashes, by beating against the overlying stratum of water, forces such rapid upward movement that the level above is forced bodily upward, it may be several hundred meters. But the fluid medium is continuous and presses in on all sides, and is therefore drawn upward on all sides about the base of the cone to supply the uprush of water. The currents thus forced with enormous violence are shown in the figure. The drawing upward of the water about the base of the cone causes the inflow of water from the bed of the sea towards the base to maintain the upward movement, following the upheaval and explosion of the volcano. Thus the water near the shore some distance away is sucked down in the general lowering of the level and the sea is observed to slowly recede at the shore. All this is done in a short time, say 30 minutes, and then follows the sea wave which has taken form owing to the forcing up of the water over the volcano, thus forming the crest, and its withdrawal from the shore, forming the trough.

The water heaved up gradually settles and the wave approaches the shore often with a velocity of something like eight kms. per minute and thus sweeps everything before it. It then oscillates back and forth with period of some 60 minutes, and for a day or two the sea may continue to be agitated with appalling violence, and the wave propagated to the remotest parts of the earth.

If an observer were to witness such an earthquake in a region where the shore was steep and the sea of uniform depth, and should note the time of the sea wave and the direction of the normal to the wave front as it first returns, he would have a very approximate means of locating the situation of the new submarine volcano. It would lie on the normal to the circular wave front, and at a distance corresponding to the time of arrival in a sea of the given depth.

The interval τ required for the oscillation of the wave being known, the theory of the wave motion could be worked out by the general formula[1] for a wave of any length λ and any depth of the water k,

$$\tau^2 = \frac{2\pi\lambda}{g} \frac{\varepsilon^{\frac{4\pi k}{\lambda}} + 1}{\varepsilon^{\frac{4\pi k}{\lambda}} - 1} \qquad (1)$$

Perhaps it could be found with sufficient approximation by the more special forms, in which the velocity becomes, when the wave is long compared to depth of the water:

$$V = \sqrt{gk}, \text{ or } V = \sqrt{\frac{g}{2k}(k+E)(2k+E)}; \qquad (2)^{[2]}$$

E being the height of the crest of the wave above the normal level of the water.

In this way we could find not only the distance of the eruption from the observer, but the direction, so as to fix its place with con-

[1] Airy, "Tides and Waves," Art. 169.

[2] Report of Committee of the Royal Society on the Krakatoa Eruption, p. 94.

siderable accuracy. If the depth is not uniform, but the topography of the ocean basin known, the observer would still be able to locate the hypothetical submarine volcano with considerable precision.[1]

Within historical times several submarine volcanoes have been observed to rise above the sea about South America and elsewhere, in places where the depth was small. From the circumstances that the sea is generally very deep off the Chilian and Peruvian coast, where the most violent earthquakes occur, one would expect but very few of these volcanoes to reach the surface. Yet the large number of sea waves following violent earthquakes may afford us some idea of the activity of submarine earthquakes and perhaps volcanoes in that part of the world. It is probable that not less than one hundred such earthquakes with sea waves occur along the South American coast in a century, and of these not less than ten have done great damage.

If the supposed eruption is some distance out at sea, the effect on shore would be small, because the level is not so much changed, owing to the great body of the intervening water. Also, when a violent earthquake occurs and but slight recession of the water is noted, followed by a wave after considerable interval, the indications would point to a great eruption at considerable distance. On the other hand, if the recession of the water is quick and the wave returns after a short interval, the eruption should be comparatively near the shore. Thus by a study of the waves observed the place and character of the eruption may be approximately determined.

In some cases the sea is said to be bodily upheaved, and rises with the utmost suddenness. In such cases the volcano may be very near shore, or the sea bottom may be upheaved in the form of a ridge or cone without submarine eruption. Since the earthquakes under the sea are very numerous, there is a great probability that all these movements of the sea should be observed occasionally.

Major Dutton adopts the view that the sea bottom sinks when the sea withdraws from the shore, and I also consider this the most probable cause in the great majority of cases. It is the more logical to accept this view since we now see how a sinking of the

[1] If such an eruption occurred the surface of the sea would be likely to show evidence of it, by ejected pumice, ashes, and other volcanic debris.

bottom can take place by natural process. So long as there was no means of explaining the subsidence of the bottom as a part of a general process in nature, the acceptance of such a violent hypothesis presented great difficulty.

To make entirely clear how collapse of the bottom may occur after the expulsion of the steam-saturated lava from under the bed of the Andean trough, we may observe that the release of the intense pent-up pressure must tend to produce a sudden and somewhat violent cooling in the stratum from which the lava is expelled. Its support of the overlying bed of the ocean trough is thus largely withdrawn, and sinking may easily follow. If this does not happen in every case (and we have no reason to think it so frequent an occurrence), it would probably follow at certain intervals, when the successive expulsions of material have reduced the underlying stratum of lava to a state of small density, in which the medium is filled very largely with bubbles of steam and therefore rapidly cooled when the pressure is released by an ejection of lava. This gives, I think, a simple conception of a self-adjusting system, such as is so often found in nature, by which the continuous process of expulsion of lava may go on, and the level of the sea bottom be adjusted automatically. But whether this is the exact process or some improvement may be suggested when our knowledge is more extended, it is clear that some such automatic mechanism is at work, and that it has operated in similar troughs all over the world throughout geological history.

As the water did not withdraw and later return as a great wave during the recent San Francisco and Valparaiso earthquakes, we know that the sea bottom did not sink in the case of either of these great disturbances. The expulsion of the lava, however, must leave the sea bottom less stable and increase the probability of its sinking when the next severe earthquakes occur at these places. As the San Francisco earthquake was much less severe than that at Valparaiso, the probability of the sea bottom sinking off the Californian coast is much less than off the coast of Chili; yet such a subsidence with the accompanying seismic sea wave is sure to come sooner or later in all places subject to heavy earthquakes. In 1812 the whole of southern California was severely shaken by earthquakes; on December 8, the water withdrew from the shore at Santa Barbara, and after a short interval returned as a great wave, which overflowed the coast and did much damage to life and property. All cities situated on such coasts should be prepared for the emergency of a seismic sea wave—that is, there should be a place of refuge for the people, and houses thus exposed to the inundations of the sea should not contain treasures and historical articles which cannot be replaced. A museum, for example, should never be built in such an exposed situation.

Perhaps a few words may be added in regard to the handling of ships, so many of which have been lost in the past, owing to the mystery surrounding these great waves. In South America the people have learned by bitter experience that when an earthquake occurs the first thing to do is to watch the sea. If it begins to withdraw from the shore they at once flee to high ground, for they know that the wave will follow. This same principle is eminently applicable to commanders of ships in the harbor. On the first indication of the retreat of the water from the shore the ships should be headed with all possible speed for the open sea. For if the ships remain in the harbor they may soon be stranded and unable to move, and sure to be carried inland when the wave returns; whereas if an effort is made to get out to sea, the ships may ride over the wave without difficulty and suffer no damage whatever. This rule is easily applied to all steam ships, whether belonging to the navy or merchant marine. Sailing vessels, being less under control than steamships, might be unable to escape in some cases; yet, if the state of the wind gave them the requisite motive power, even they might make the open sea. A wave does not come immediately after an earthquake, but something like half an hour or an hour afterwards, and this usually gives time for escape. After the sea bottom subsides, the water must flow from the shore into the depression, and then when the water piles up, it must again flow back to land to produce the wave; and if the ships are properly handled in this interval, most of them will escape undamaged.

IX. Concluded Theory of Volcanoes.

§ 42. *Other theories of volcanic action.*

The four fundamental facts mentioned in § 10 have been fully considered, and we have found that the hypothesis of the penetration of sea water into the crust of the earth affords a natural and satisfactory explanation of all volcanic phenomena. Such hypotheses as the following: (1) Lava flowing out of a molten interior, is contradicted by the rise and fall of the columns of lava in volcanoes, as if forced up by the elastic pressure of steam, which also escapes in eruptions; (2) molten reservoirs, contradicted by the same phenomena; and moreover neither (1) nor (2) enables us to account for the observed distribution of volcanoes; (3) melting by relief of pressure, and (4) melting by crushing, encounter the same difficulties, and others besides. None of these four hypotheses can be seriously considered.

There remains Major Dutton's recent suggestion that radium is the exciting cause. But the researches of the Hon. R. J. Strutt have shown that all the principal rocks of the earth's crust, especially granite, contain large quantities of radium, and since these rocks underlie all the continents, we should expect abundant active volcanoes everywhere inland if radium were the exciting cause, whereas in fact they appear in the depths of the sea or along the shores of the oceans. The cause of volcanic action is thus narrowed down to the penetration of water into the heated rocks of the earth's crust, and all other hypotheses may be unhesitatingly rejected.

We shall now adduce some further considerations bearing on the aqueo-igneous theory, with a view of throwing additional light upon particular phenomena.

§ 43. *Certain objections to the theory of the penetration of sea water.*

The beginning of this theory may be traced back to Lucretius, and perhaps to Aristotle,[1] and hence we shall first answer two objections which have been urged against it.

First, it is held that the temperatures of the lavas are too high, 2,000° to 3,000°, whereas one would expect the temperature to be

[1] In more recent times it has been treated by Sir J. Prestwich, in a paper "On the agency of water in volcanic eruptions," Proc. Roy Soc., April 16, 1885.

no higher than from 700° to 1,000°. A sufficient answer to this objection is the pressure within the earth's crust, which removes the depth of fusion to a lower layer where the temperature is higher; and, moreover, in all eruptions the temperature is no doubt greatly raised by the violent churning the lava receives before reaching the orifice of the volcano, and by superheated steam escaping through it. The lava would naturally flow from that depth at which motion under the earth's crust is easiest, and the temperature observed is therefore about what should be expected.

Second, it is held that the fractured portion of the earth's crust which would permit a ready penetration of water is confined to a layer not more than five or six miles deep, the great pressure lower down operating to close all crevices; and it is therefore claimed that water going down fifteen or twenty miles would penetrate the remaining ten to fourteen miles of unbroken rock with great difficulty. In answer to this objection it may be said that the depth to which rocks are fractured is not certainly known; but whatever it may be, Daubrée's experiments show that the force of capillarity may cause the water and steam to keep on descending till the vapor reaches a temperature where it is rapidly absorbed and diffused among the rock, just as gases are in hot steel; and when the vapor becomes superheated its explosive violence is greatly increased, and hence this also would tend to raise the observed temperature of the lava, because it is chiefly the hotter lava, still further heated in ejection, which would be forced out of volcanoes.

These objections, therefore, present no serious difficulty to the theory that volcanic action depends on nothing but the penetration of sea water.

It is sometimes said that earthquakes accompanying volcanic eruptions are shallow, and it has therefore been inferred that the lava comes from no great depth. Perhaps a more correct view would be to hold that the throat of the volcano does not become closed to a great depth, by partial cooling of rock since the last eruption, and the shocks naturally proceed from this point of resistance rather than from the source of the steam and lava rising beneath the volcano, which may be much deeper, and yet give no sensible indication of their movement till the resistance becomes considerable. Besides the honeycombed pumice which underlies volcanoes, it may be supposed that they frequently contain a certain number of passages out of which the pumice has been blown, some of which may become real caverns when the lava subsides after an eruption. When a new eruption begins these old passages might offer little resistance till the lava column came within a short distance of the surface, and hence the shallowness of the shocks witnessed in eruptions. The shallowness of these shocks does not prove the superficial character of the lava erupted; on the contrary the earthquake shocks felt over the whole region around every active volcano shows that the subterranean disturbances arise in a layer which acts as fluid just beneath the crust. The forces developing in this layer find their relief in the eruption of steam and lava from the volcano.

§ 44. *The origin of volcanic ashes due principally to the breaking and grinding up of pumice.*

In his useful work on the "Volcanoes of North America," the late Professor Russell, of the University of Michigan, makes the following explanation of the origin of volcanic ashes (pp. 75–76):

"*Sheets of Volcanic Sand and Dust.*—In the case of volcanic eruptions of the explosive type, the steam occluded in the lava expands as external pressure is relieved; this expansion is frequently so violent that the rock is disintegrated and the fragments projected high in the air. Besides this primary mode of reducing the lava to fragments, and much of it to the condition of dust, the larger fragments as they are shot upwards with a velocity in some instances even greater than the initial velocity of shells fired from modern rifle-cannon, strike against one another and against falling fragments, and are shattered, thus tending to increase the quantity of fine dust-like particles produced. While much fine material originates thus, and is carried away by the wind, many of the fragments that escape comminution fall into the the crater from which they were thrown and are again violently ejected, thus multiplying the chances of their being reduced to powder. An eruption of the explosive type thus tends to form much fine dust, which is carried high into the air by the upward rushing steam and falls most abundantly near the place of discharge. Should a strong wind be blowing, the dust is carried to leeward of the volcano, and on reaching the earth forms a sheet, which, owing to the winnowing action of the wind, is composed of finer and finer fragments, the greater the distance from the volcano."

Professor Russell appreciated more fully than many geologists the necessity of explaining the enormous clouds of dust which arise from volcanoes, but it is difficult to escape the impression that his explanation is somewhat labored. It would be more natural to say that a volcanic mountain is underlaid and filled with pumice and when the explosions become violent some of this porous material is ground up and blown out as dust. Much of it may already be in the form of powder from former earthquake shocks when the mountain was packed with pumice, and simply requires to be blown out; and hence the vast clouds which obscure the sun and darken the earth for hundreds of miles! If the rock broken up by the explosion were solid, as supposed by Russell, it would be less easy to account for the enormous outpourings of ashes, observed in such volcanoes as Hecla, Ætna, Vesuvius and Conseguina. Solid rocks would produce lapillæ and sand rather than fine ashes, which result from the breaking up of pumice with very thin bubbles.

When lava is forced up in the throat of a volcano some of it may run out, relieving the pressure which raised it, and the rest then sinks back into some of the passages which lead to the throat of the volcano. There may be, and in general probably are, several of these passages, unequally opened at different times, and the lava is forced up from some of them. After the lava is poured out and subsides, other passages formerly closed may be opened and eject vast quantities of volcanic ashes without encountering any molten rock whatever. It would be a great mistake to suppose that all ashes which pour from a volcano are forced through a layer of liquid lava before ejection. If the ashes were forced through a layer of liquid they would be red hot when cast out, and such heat would give the particles a ruddy glow. As a general rule, such a glow is not observed, and hence the theory that the ashes are ejected through a layer of liquid is untenable. The outpouring of lava is only a part of the operations of a volcano; the ejection of vapor, ashes and pumice being, perhaps, even more important. Steam is the one force which has to be relieved, and the other substances ejected are incidental thereto.

In his well-known on "Geology" (fourth edition, 1903), p. 173, Sir Archibald Geikie says:

". . . The finest dust is in a state of extremely minute subdivision. When examined under the microscope, it is sometimes found to consist not only of minute crystals and microlites, but of volcanic glass, which may be observed adhering to the microlites or crystals round which it flowed when still part of the fluid lava. The presence of minutely cellular fragments is characteristic of most volcanic fragmental rocks, and this structure may commonly be observed in the microscopic fragments and filaments of glass. A characteristic feature of these minute fragments is the frequent occurrence among them of semi-circular or elliptical ('hour-glass') shapes, which evidently represent the sides of vesicles or pores that enclosed vapour or gas in the molten rock, and were disrupted and blown out during volcanic explosions."

§ 45. *On the supposed absence of volcanoes in the Alps and Himalayas, and on the former existence of these vents in the interior of continents.*

It is frequently remarked that volcanoes do not appear in the Alps and Himalayas, and the inference has been drawn that no volcanoes originated in the formation of these great mountain ranges. But it is well known that at some time in the past geological ages volcanoes existed in almost every part of every country, and mountain chains like the Alps and Himalayas are no exceptions to the general rule. Professor Suess ("Face of the Earth," Vol. I, pp. 201–274) mentions some volcanoes formerly active in the Alps, and undoubtedly similar vents once existed in the Himalayas. In the course of time nearly all surface trace of eruptions is lost where the glaciation, denudation and sedimentation are active, as in the Himalayas. When we consider how imperfect our knowledge of those mountains is, not only because they are high, but also inaccessible to exploration, the failure up to this time to find extinct volcanoes or their products is not remarkable. Craters are soon covered by ice and worn down by the grinding action of glaciers, while their ashes and lavas are equally covered and lost from view.

Major Dutton justly remarks that the regions which have been exempt from volcanoes are small in comparison with those which have had them; and he observes that going back to early Tertiary times we find them occurring where they have long been extinct.

"The grandest volcanic field in the world was central and southern India in Cretaceous times, when there was not a volcano in all Europe, and extremely few in North and South America. In the Jura-Trias, the Appalachian region, from Labrador to the Gulf of Mexico, bristled with them, and vast plateaux of lava were outpoured. In Paleozoic, they abounded in the region of the Great Lakes, in Missouri, in Arkansas, and in eastern Texas. There is hardly a county or bailiwick on the whole mundane sphere which has not had its volcanic cycle at some time or other, and there are many which have had two, three, four or five cycles. Volcanoes are not local phenomena, nor yet are they strictly universal. But they come very near being universal. I think that Charles Darwin's observation that they are associated with regions of elevation is very generally sustained, even in the depths of the ocean."

These remarks of Major Dutton, communicated to the writer in a private letter, are of unusual interest. At the present time we have no active volcano in the world more than 100 miles from the sea or equivalent large body of water. It has been remarked that Mt. Demavend is about 320 miles from the Mediterranean, but only about 50 miles from the Caspian Sea, which is a deep body of salt water. In the same way Jorullo in Mexico is about 80 miles from the Pacific coast, but it has never been active since the first outbreak in 1759. Some of the volcanoes in the eastern range of the Andes of Bolivia may be over 100 miles from the sea, but they are much nearer Lake Titicaca and the terrible tropical rains which constantly drench the eastern slopes of the Andes.

Thus all active volcanoes, to the number of about 400, are very near the sea or equivalent large lakes. In the interior of continents they die out for lack of adequate water supply. Unfortunately, we do not know the contours of the sea in past geological ages very accurately, but from Major Dutton's remarks, quoted above, it seems probable that volcanoes have always developed in the neighborhood of the sea and died out when the water receded to a considerable distance from them. This is well illustrated by the extinct volcanoes now found in the western part of the United States. Thus volcanoes of former ages seem to follow the same law as those now active.

The present distribution of volcanoes proves conclusively that they depend upon the sea. The erupting force is shown to be steam by the great preponderance (999 parts in 1,000) which that vapor has over all others.

The progressive extinction of volcanoes in the interior of continents is, therefore, clearly intelligible. Not only do the volcanoes die out for lack of motive power to keep open the orifices, but the earthquakes also famish in the same way, though to a lesser degree, because their explosive force is distributed over a wider area and does not require to be so concentrated. Unless a volcano keeps moderately active it becomes permanently closed by lava hardening in its throat; yet earthquakes which have no surface outlet may successfully maintain a languid existence on a small supply of water, and hence they may continue to be felt in a region long after all volcanoes have been extinguished.

§ 46. *Explanation of immense outflows of lava such as are seen in the plateau of Deccan and in Oregon and Utah.*

For a number of years it has been a subject of remark among geologists that the largest lava flows are not the output of volcanoes, but of immense fissures which opened in the earth's crust and permitted the welling forth of vast quantities of molten rock. Sir Archibald Geikie (cf. Suess, Vol. I, p. 145) emphasized this view as long ago as 1880. In recent years this theory of the origin of the immense deposits of sheet lava seen in the region of the Columbia River in Oregon and in Utah, as well as in the great tableland of Deccan in India, has been very generally adopted. In all such cases fissures no doubt opened and poured forth the molten rock throughout their length. The subsidence of considerable areas of the earth's crust may have contributed to this outflow, and different degrees of liquidity are invoked to explain the observed phenomena. Reyer suggests (cf. Geikie's "Geology," Vol. I, p. 301) that the degree of saturation with gases and vapors may have influenced the form of eruption, volcanic discharges resulting when the impregnation was strong enough to cause eruption, and tranquil outpourings when the rock is but feebly saturated with explosive gases.

Major Dutton thinks differences of temperature as well as chemical differences may have been more important in giving the great lava flows their peculiar aspects. In regard to these outflows in general, I believe that the crust cracked open on account of the relative movement of neighboring portions. There are many ways in which this could occur. If there were any appreciable tangential pressure between two portions of the crust, the outpouring of lava would be less easy; but since we abandon the contraction theory and deny that the mountains are due to the shrinkage of the crust, there is on this hypothesis no pressure between the two portions of the crust except that due to their weight when resting side by side. If, therefore, the subterranean movements under two neighboring parts should be such as to force a fault apart, there would be nothing to prevent the lava from rising and pouring forth.

In the valley of the Ganges the earthquake thrusts were towards the Himalayas, and at some period in the upheaval of these mountains the crust may have been cracked and also so pulled apart as to allow the great lava flows observed in the plateau of Deccan. Much of this may have occurred when the peninsula of India was still under the sea. No doubt the great lava flows of Oregon and Utah were similar in character, but the details of the process must be left to future investigation.

§ 47. *On the vapors exhaled by volcanoes.*

We have seen that, according to Geikie, 999 parts in 1,000 of the vapors emitted by volcanoes is composed of steam, and have concluded that this is the only original vapor operating under the earth's crust. For the one-thousandth part of other gases such as sulphurous oxide, carbon dioxide, hydrochloric acid, et cetera, may well be derived from the heated rocks when saturated with steam, without any other original gas existing in the earth. If any other gas except steam were really active in the earth, either under the volvanoes or in remote regions which are disturbed by earthquakes, we may be very sure that at some of the volcanoes some of this gas would escape and we should be able to recognize it. As such escape does not occur we may be quite sure that steam is the only original vapor operating within the earth.

The question of the dissociation of water vapor by the intense heat of subterranean lava is also worthy of remark. It has been found by analyses of the vapors escaping from Thera, where the outlets are generally submarine, that the water gases are dissociated. Immediately over the focus of eruption free hydrogen formed 30 per cent. of the gases emitted. In general the free hydrogen is fully twice as abundant as the free oxygen, so that the mixture on coming in contact with a burning body at once ignites with a sharp explosion. A considerable quantity of free nitrogen is also present, and traces of other gases. Fouqué, who has given most attention to this subject, infers that the water-vapor of volcanic vents may exist in a state of dissociation in the magma just beneath the earth's crust. The free nitrogen is supposed to be derived from the air absorbed in the water which percolates downward.

The question of the existence of true volcanic flames was first settled by the observations of Fouqué, who showed that true flames may arise when the free gaseous mixtures are ignited by red hot stones from the volcano or by the strokes of lightning which play so actively about the orifice of a volcano in eruption. No doubt the dreadful tongues of fire so often seen to radiate from erupting volcanoes are to be explained very largely by the ignition of free gases by thunderbolts produced by the condensation of clouds of aqueous vapor.

§ 48. *Strabo speaks of the volcanoes as safety valves.*

In his "Principles of Geology," 12 edition, Vol. 1, p. 25, Lyell remarks that the gifted Amasean geographer, Strabo, alluding to the tradition that Sicily had been separated by a convulsion from Italy, adds (Lib. vl, p. 396, edit. Almelov. Amst. 1707) that in his time the land near the sea in those parts was rarely shaken by earthquakes, since open orifices exist whereby fire and burning matter and water escape; but formerly, when the volcanoes of Ætna, the Lapari Islands, Ischia and others were closed up, the imprisoned fire and wind might have produced far more vehement movements. "The doctrine, therefore," continues Lyell, "that volcanoes are safety valves, and that the subterranean convulsions are probably most violent when first the volcanic energy shifts itself to a new quarter, is not modern."

X. Concluded Theory of Earthquakes.

§ 49. *All important earthquakes due to the action of explosive forces within or just under the earth's crust.*

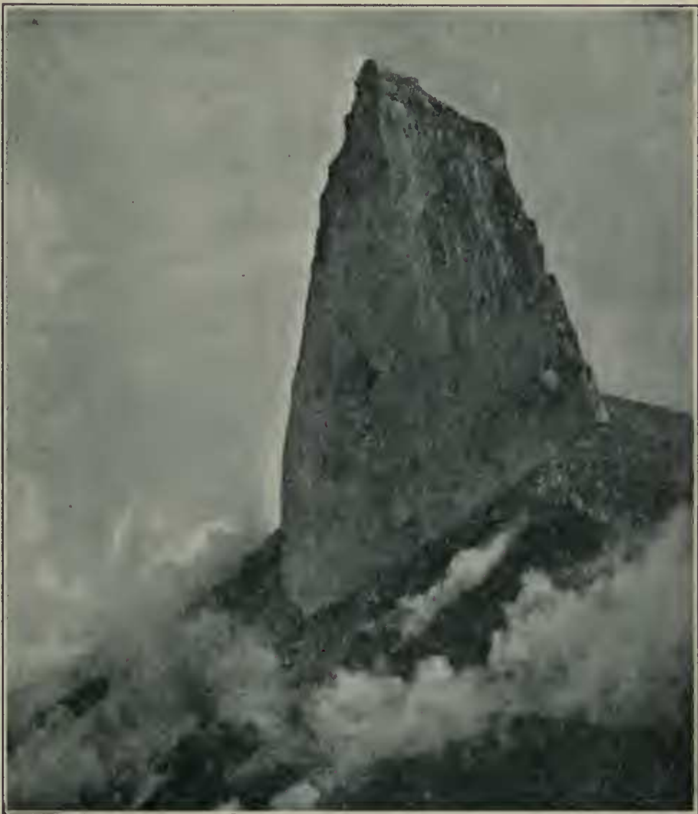
Major Dutton seems to have had an inkling of the process here involved when he wrote the following ("Earthquakes," p. 49–50):

"It remains now to refer to the possibility that many quakes whose origin is unknown, or extremely doubtful, may, after all, be volcanic. This must be fully admitted, and indeed, it is in many cases highly probable. Evidences that volcanic action has taken place in the depths of the earth without visible, permanent results on the surface abound in ancient rock exposures. Formations of great geological age, once deeply buried and brought to daylight by secular denudation, show that lavas have penetrated surrounding rock-masses in many astonishing ways. Sometimes they have intruded between strata, lifting or floating up the overlying beds without any indication of escaping to the surface. Sometimes the lava breaks across a series of strata and finds its way into the partings between higher beds. Or it forces its way into a fissure to form a dyke which may never reach the surface. In one place a long arm or sheet of lava has in a most surprising and inexplicable manner thrust itself into the enveloping rock-mass, and in the older of metamorphic rocks these offshoots or apophyses cross each other in great numbers and form a tangled network of intrusive dykes. In other places the intruded lava formed immense lenticular masses (laccolites), which have domed up the overlying strata into mountain masses. These intrusions, almost infinitely varied in form and condition, are often, in fact usually, inexplicable as mechanical problems, but their reality is vouched for by the evidence of our senses. What concerns us here is the great energy which they suggest and their adequacy to generate in the rocks those sudden, elastic displacements which are the real initiatory impulses of an earthquake. They assure us that a great deal of volcanic action has transpired in past ages far underground, which makes no other sign at the surface than those vibrations which we call an earthquake."

The blowing out of a huge obelisk of granite some 300 meters long and 120 meters in diameter but too large to get through the orifice of Mount Pelée, and which therefore hung in the mouth of that volcano, while the cone itself was split on all sides by the fearful force of the explosion which had ejected the plug of granite from the roots of the volcano, affords an excellent and familiar example of what may be done by volcanic forces. This obelisk is illustrated in the *National Geographic Magazine* for August, 1906, by photographs made by Professor A. Heilprin, who gives an excellent account of the history of the obelisk and its gradual disintegration. If these forces are suddenly arrested, as they are in all earthquakes which do not produce immediate eruptions, the shock is taken up by the surrounding earth and we have a violent earthquake which may be felt all over the world.

If the explosions are no larger than those involved in the eruptions of geysers the results are mere microseisms or earth tremors, interesting enough to be sure, but of an unimportant character. A really serious earthquake, to be felt all over the world, implies the exertion of the most tremendous forces, and the way in which these forces set the earth particles vibrating shows that they must depend primarily upon the explosive power of steam-saturated lava at great temperature. The result is a violent shaking of the whole overlying layers of rock and the occasional upheaval of volcanoes where the strata are fractured and weak. The very way in which the earth twists, heaves, labors and vibrates shows the awfulness of the pent-up

FIG. 15.



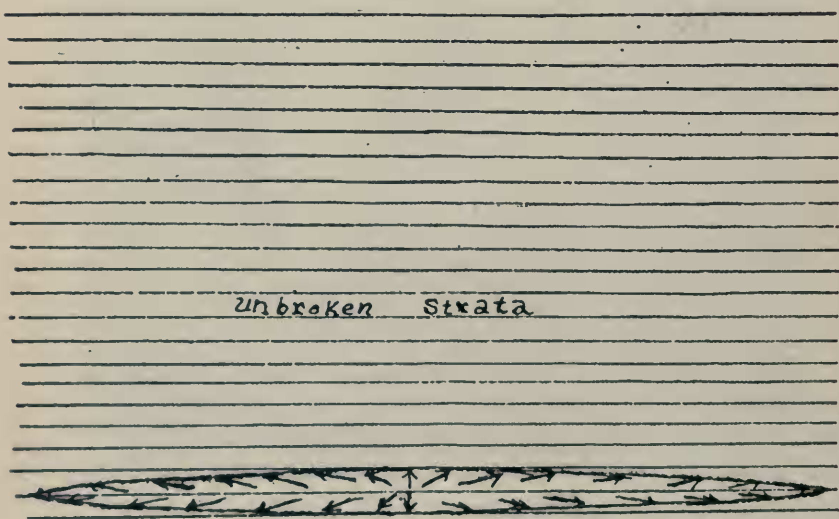
The shattered obelisk of Mt. Pelée, photograph taken by Professor Angelo Heilprin.

forces; and it is no wonder that such shaking should throw down buildings, settle soft "made" ground, leaving fissures where it is shaken down, and even cause faults in the overlying mountains to slip or open.

§ 50. *But the movements of faults are the effects of the earthquake, not the cause.*

Such small slips as are usually observed would not account for the enormous forces shown in the accompanying earthquakes. Besides the horizontal form of the vibrations, so frequently shown, as more fully pointed out in § 51, could not be explained by simple subsidence. Yet it is evident that these faults may easily result from the mighty steam pressure which has shaken the earth sufficiently to break the layers of rock, and give relief to the pent-up forces. In so-called tectonic earthquakes the forces usually are greater than those involved in volcanic action, because the whole body of the overlying strata must be shaken to afford the smallest relief, but are seldom so concentrated as would be required for the upheaval of a new volcano through the entire depth of the unbroken crust. If the crust is already badly fractured or breaks more easily than it gives relief

Fig. 16.



when shaken, sometimes new volcanoes actually break forth, especially under the sea, where the explosive forces are greatest.

When we consider the terrific shock required to break all the horizontal strata in a situation where the imprisoned forces are deep-seated we can readily imagine that yielding will often occur through condensation of soft rocks, through tightening up of crevices, joints and faults, and sometimes by uplifts of all the strata, affording room for the injection of a layer of lava of large extent, or its diffusion by spreading into surrounding areas. The movement of the fluid is shown by the arrows in the figure. In that case the eruptions may be either subterranean or submarine, as in the elevation of the Chilean coast noticed by Darwin and Fitzroy in 1835.

On the theory of faults, as now held, it is difficult if not impossible to account for the observed elevations. It is perhaps true that elevations apparently are rarer than subsidences, yet they are much more significant and furnish a better criterion of the forces at work, since many subsidences on land are due to settling of soft ground which has never been consolidated under pressure. But we must remember that only very few absolute levels are accurately known and still fewer remeasured after an earthquake; and therefore while subsidences appear to be the more general phenomena, especially in regions of soft earth, one may well be very doubtful whether, in the case of hard ground, elevations, though mostly unnoticed because there is no easy means of measurement, do not really predominate. Reasons connected with the mode of formation of mountains and the elevation of coast lines, given heretofore, point strongly to elevation as the more general movement in nature. For it is this movement which has uplifted both mountains and continents, and we cannot suppose that it has ceased to be the dominant influence, though it generally escapes notice, because we have no means of detecting it, while local subsidences frequently are easily recognized, and we naturally look for it because of the frequent shaking down of "made" ground.

In most earthquakes the heaving force is distributed over a considerable area, and when the stress becomes great enough a movement takes place along the nearest fault line—the path of least resistance—and the observer who sees the slip says the movement of the fault caused the earthquake.

The fact that most earthquakes are found to originate at a depth of from ten to twenty miles shows that the epicentrum is below the depth at which the strata have any opportunity of moving; and the proof that the shock usually comes from an *area* and not from a point or from a line, shows that the shock depends on an explosive stress spread over a considerable region, and in no way depends on dislocational or fault movements, which are always quite superficial.

§ 51. *Explanation of the rotatory motion observed during an earthquake.*

If we consider with attention how simple the motion of subsidence or elevation, in a supposed fault, really is, we shall perceive that such displacement cannot give the earth particle an appreciable rotatory motion. For the two sides of a fault are conceived as continuous and unbroken parts of the earth's crust, and thus securely fixed at their backs, and moving only at their faces, where the fracture exists. The motion is essentially like that of a double cellar door opening or closing very slightly in the middle, with rigid hinges at their backs. They can only go up or down together, or one up and one down, with little or no horizontal motion; and thus cannot produce a revolving tremor when opened or shut.

It is exactly so with the slipping of a supposed fault in the earth's crust. It is mechanically inconceivable how the vertical subsidence of a fault could give the earth particle a revolving motion in the plane of the horizon. At most, such a slip could produce an up-and-down oscillation, with the path of the ellipse described by the particle very nearly in the vertical plane.

Now the earthquake which destroyed San Francisco gave the earth particle a large and conspicuous rotation almost parallel to the horizon; it was "a twister," and this rotatory character was so marked as to attract instant attention. The conspicuous rotation and the difficulty of explaining such a motion by the theory of faults, as ordinarily stated, led the writer to question the validity of that theory. As most of the violent earthquakes have both rotation and vertical movement, it is evident that the difficulty felt in explaining the San Francisco earthquake is very generally encountered in earthquake phenomena.

It seems to have escaped the attention of seismologists that rotatory earthquakes require explanation, and the theory of subsidences of rocks and faults is incapable of furnishing it. How then can motion of rotation be accounted for?

To answer this question in the simplest way we may recall that there are many impulses which can give a motion of rotation, either by direct impact or by the "kick back," or recoil of reaction. If, for example, we suppose an orifice to be forced through an underlying or overlying layer of rock so that lava escapes under great pressure, but the resistance is unequal in the different directions, it is evident that as the imprisoned matter expands or explodes, the reactions in the different directions will be inversely as the corresponding resistances to the escaping fluid. In general the explosion will give a rotation to the surrounding particles, since the moment

FIG. 17.

Seismographic record of the San Francisco Earthquake, April 18, 1906, taken at the Chabot Observatory, Oakland, California, Professor Charles Burkhalter, Director.

of the resistances will not pass exactly through the center of the exploding mass, and the rotation is as likely or more likely to be in the horizontal plane than in any other. If the explosion or rapid diffusion of steam pressure takes place in stratified rock, the strata are fairly sure to be approximately horizontal; but no doubt most all violent earthquakes occur at greater depths, and no one can predict the inequalities of the encountered resistance. It would all depend on the shape and relative situation of the expanding matter in relation to the surrounding rock, which would also be at high temperature.

As the reservoir of steam-saturated lava would rarely be spherical and would usually be a layer, as we have seen in part IV, and several separate and distinct reservoirs might develop near one another, a streaming of the released matter, when the walls yielded and the strain is released and the fluid quickly adjusted itself to the new surroundings, would almost always produce some kind of rotatory motion, and it would always lie in a plane between the horizon and the zenith. If the layers were complex or of irregular figure this movement might be made up of several parts and the adjustment occupy several seconds, and possibly minutes, of time, even when the forces are enormous and the motion correspondingly rapid.

The successive powerful impulses or blows imparted to the surrounding earth might be of unequal intensity and not all in the same plane, and moreover the vibration would continue for a short time after the internal movement had ceased, on account of the elasticity of the rocks of the earth's crust. Lava saturated with superheated steam would behave essentially like steam in an exploding boiler, because it would give body and momentum to the spreading steam and be capable of transmitting shocks of appalling violence.

This gives us a conception not only of the process involved in an earthquake, but also of how the irregularities noted by seismographs might be accounted for; and when we recall that the subterranean boiler might surpass the largest mountain in size, or be flattened into an immense disc[1] of slight thickness, with vent chiefly or wholly at the sides, we can easily understand the terrific forces which shake the whole earth when once the surrounding walls give way or a fault moves, so that an explosion and diffusion of the lava is effected.

It must be assumed, for reasons already fully developed, that sensible readjustment and motion of large masses of steam-saturated

[1] It is found by investigation that many of the tectonic earthquakes originate in an area of considerable extent.

lava or molten rock take place in every important earthquake; confining walls and caverns of unequal pressure are reduced to one common strain, and the resulting motion involves rapidly acting and enormously powerful forces, which may shake the whole earth and sometimes crack or derange the overlying strata of rocks many kilometers deep.

§ 52. *Explanation of the New Madrid earthquake and some other earthquakes often classed as tectonic.*

In his excellent work on "Earthquakes" Major Dutton remarks that the New Madrid earthquake could not be said to have any real depth, although he says it was strongly felt as far east as Boston, and in fact nearly all over the United States. His reasoning is based upon the supposition that it was due to the sinking of some bottom land, which seems to be quite unjustifiable. The subsidences happened, indeed, but we shall find the best reasons for holding that they were produced by explosions within the earth, which must therefore have been at least ten miles deep. Unless it had been of about this depth this earthquake could not have been so strongly felt throughout so wide an area of country.

It seems probable that the water seeped down from the Mississippi River, which always overflowed badly here, and worse in prehistoric times than now, because the country was then much more heavily timbered; or the seepage was a survival effect of the fractures of the Ozark Mountains, from the time when the Gulf of Mexico extended far up the river, and thus was beginning to form a sea valley about parallel to the general trend of the Ozark Mountains which were left unfinished.

Thus the cause producing this earthquake is apparently not different from those at Charleston, San Francisco and many other places which have experienced so-called tectonic earthquakes.

The most trustworthy accounts of the New Madrid earthquake show that it was the most violent and destructive earthquake ever felt in the United States. Lyell has given an excellent account of this earthquake, based upon observations gathered during a personal visit in 1846, but the records here followed are of still earlier date.

Over a region of 300 miles in length, but especially from the mouth of the Ohio to that of the St. Francis River, the ground rose and sank in great undulations; trees had to be felled across the fissures for the preservation of the inhabitants, and lakes were formed and drained again, and many large streams changed their channels and even their courses. Physical evidences of this terrible convulsion are still seen near New Madrid, where the loose land had settled so much as to form swamps, leaving great cypress and other trees so deep in the water that they died (some were entirely submerged), and in many places still remain to show where the water rose in 1811. Little Prairie, now called Caruthersville, 20 miles below New Madrid, was considered the center of greatest violence. The first severe earthquake occurred on the night of December 16, 2:15 a. m., and shook severely the whole region of the Ohio, Mississippi and Missouri rivers, as far north as the Lakes, as far east as the Alleghanies, south to the gulf, and west to the Rocky Mountains.

One of the best accounts of this great earthquake, drawn from contemporary sources of information, is that given by Professor G. C. Broadhead, of the University of Missouri, in the *American Geologist* for August, 1902. The leading points may be summarized thus:

1. After the first severe shock at 2:15 in the night, smaller shocks followed, and at 7 a. m., December 16, 1811, came a much more severe shock; then came lighter shocks daily or oftener, until January 23, 1812, when an extremely severe shock was felt; continual agitations were felt till February 4, which brought another severe shock, and four more followed next day; and on February 7, at 4 p. m., came one so much more violent than the preceding that it was called "the hard shock." Hundreds and even thousands of smaller after-shocks have continued at irregular intervals to the present time. "Two series of the (original) concussions were particularly terrible."

2. Thus there were at least eight very severe shocks, each of which did great damage and spread devastation far and wide.

3. The eye-witnesses generally agree that these severe shocks were preceded by heavy subterranean thunder; "a loud roaring sound like steam escaping from a boiler"; "distant rumbling sounds succeeded by discharges as if a thousand pieces of artillery were

suddenly exploded"; "a rumbling like distant thunder"; "an awful noise resembling loud and distant thunder, but more hoarse and vibrating," are some of the descriptions.

4. All the severe shocks were accompanied by the escape of sulphurous vapors from the great fissures which opened in the earth; and on December 16, after 7 a. m., the severe shock was accompanied by total darkness till sunrise; in one of the shocks witnessed by J. J. Audubon near Henderson, Kentucky, he took the cloud of vapor on the western horizon for a rising storm; and in general the eye-witnesses in Missouri agree that flashes were frequently observed as if these vapors were generating electric discharges in the air.

5. The severe earthquake shock of February 7, 1812, lasted four minutes, according to Jarred Brooks of Louisville, Kentucky, who seems to have given much attention to these phenomena, and classified them carefully. He said: "It seemed as if the surface of the earth was afloat and set in motion by a slight application of immense power, then a boiling action succeeded, houses oscillate, gables and chimneys of many houses are thrown down."

6. Great fissures running nearly north and south (Lyell's measurement in 1846 made the direction from 10° to 45° W. of N.) were formed five miles long, ten feet wide, and four feet deep, by the great undulations which came from the west; hills were sunk, forests inundated, lakes drained, swamps formed, the bed of the Mississippi River upheaved so that its waters backed up for a time, then came booming on, broke over and swept everything before them, and nearly all the shipping was destroyed; hills rose where lakes and swamps formerly stood; the waters of the Mississippi receded from its banks and then returned as a wall fifteen or twenty feet high, tearing the boats from their moorings and carrying them up a creek a quarter of a mile.

7. Water and sand, and some coal or lignite, and sulphur was ejected from the fissures, the materials being thrown forty feet high, which aided in filling the air with noxious vapors.

The ejection of this material from the ground would explain some of the noises which accompanied these earthquakes, but not all. The deep subterranean thunder preceding the shocks cannot be explained except by explosions in the earth. Some of the land was no doubt simply settled by shaking, but this will not account for the upheaval of the bed of the Mississippi River so as to make its waters flow upstream; and we seem obliged to admit that in addition to subsidence there was also elevation of ground.

The New Madrid earthquake is extremely remarkable for its numerous severe shocks and the long intervals at which they occurred, the last great shock of February 7, 1812, being the worst of all. The order of events does not harmonize so well in the tectonic theory of rock slipping as it does with Strabo's account of a volcanic outbreak near Chalcis, in Eubœa, in which the shocks ceased only after a fissure opened on the Lelantine Plain and ejected a fiery river of mud. To be sure, no lava was ejected in the New Madrid earthquake, but the phenomena resemble those described by Strabo, in which elastic vapors within the earth were seeking release. If no single outburst of lava and steam could break forth above ground the agitation might on that account continue all the longer, and an impartial study of this remarkable earthquake strongly suggests this explanation. The whole course of events is singularly inconsistent with any suggestion that mere slipping of rock or subsidence was involved.

We have examined this earthquake in detail, because it is little understood and so complex and extraordinary in respect to location and duration that it constitutes a severe test of any theory; and yet a comprehensive theory must be able to account for such phenomena without prejudice to the historical facts.

§ 53. *Other important earthquakes.*

If we examine attentively the available details of various other earthquakes which are classed as tectonic we shall find that most if not all of them give evidence of high explosive power within the earth. Under ordinary conditions it may be supposed that these forces are exerted long enough to afford partial or complete release from the strain, and then the agitation ceases or continues in the form of slight after-shocks. It is only when unlifts occur that we have direct proof of an uplifting force, the visible effect of subterranean explosive power; but it would seem that the heaving of the earth accompanying the rending of strata and breaking of rocks is a fairly obvious indication of imprisoned vapors seeking release from contact with molten rock.

In fact nearly all the recent important earthquakes of great violence, and inappropriately classed as tectonic, present strong indications of being due to steam power. It probably is not too much to say that it is doubtful if one of them could be fairly explained by mere subsidence due to the slipping of rock faults.

In almost every case it will be found that the rock slipping noted at the surface is small, while it is conceded that the chief effect must depend upon great forces exerted from deep down. This seems to be substantially admitted by most writers, who have a suspicion that the forces are singularly deep-seated and otherwise act in a strange way. The Charleston earthquake originated twelve miles below the surface, while the San Francisco earthquake will not prove to be of less depth. The Bengal-Assam earthquake of June 12, 1897, investigated by Mr. R. D. Oldham, must have had great depth, owing to the wide extent of country over which is was felt and the great intensity of the shocks. The same is true of the Mino-Owari earthquake of October 18, 1891, and all other earthquakes of high intensity which were widely felt. The Valparaiso earthquake of August 16, 1906, was among the most terrible of modern times, and it was so widely felt that the depth could hardly be less than fifteen or twenty miles.

It seems desirable to direct attention to the fact that probably not one of these great earthquakes has occurred in a region where seeping of water and formation of steam may not have been the dynamic cause. The center of the violent Bengal-Assam earthquake was under the great Bramaputra River, where it spreads to great width and drains an immense volume of water from the Himalayas. This region was originally a deep trough in the sea and has since been filled in; and owing to the great surface drainage is still essentially an inland sea not far from the Bay of Bengal, which receives also the Ganges as well as the Bramaputra. The situation is very similar to that of New Madrid, but is nearer the sea, and has the Himalayas on the north, from which the drainage is enormous. Besides there is in that region a natural survival of the forces which uplifted the Himalayas, and this ancient sea valley did most of the work involved in the raising of these mighty mountains.

If we examine the violent Japanese earthquakes we shall find that most of them, as Professor Milne says, arise under the sea near the seashore or at the heads of bays, where the influence of the sea would predominate. It seems impossible to doubt that they are due to the influence of steam formed in the earth beneath; for the island of Nipon is essentially narrow, mountainous and broken by great irregularity of topography, so that the seepage of water is easily accounted for, and more especially since the worst earthquakes are on the east coast and partly under the sea on the edge of the Tuscarora Deep, where the shore is steepest and the sea pressure greatest. Moreover, it is shown in § 33 that the whole island of Nipon has been uplifted by injections of matter expelled largely from under the bed of the Tuscarora Deep; and what is more natural than to suppose that this process is still going on? This inference in, fact is confirmed by the secular elevation of the east coast observed within the historical period.

The regions of Iberian Peninsula visited by violent earthquakes are those similarly exposed to the sea—Lisbon and the southern provinces, such as Andalusia, which are also broken and mountainous, and have been recently rising from the sea. In Italy the region of greatest and most violent disturbance is Calabria, the "toe of the boot," which is a long peninsula nearly surrounded by the sea and of remarkably fractured and broken topography. The islands of Sicily, Ischia, Lapari, Stromboli and the coast near Vesuvius is similar, and all these regions are still rising from the sea. Nearly all Greece is very broken and mountainous and it has always suffered severely from earthquakes. In Hungary, where the severe earthquake of Agram, Croatia, occurred November 9, 1880, the country is full of hot springs, indicating an abundance of underground water, and while the volcanoes have died out the earthquakes still survive. The earthquake in Silesia, June 11, 1895, occurred in a region of the same kind.

If now we turn to Central America we find it a narrow broken country with sea on both sides; and on the other side of the Pacific, New Zealand is a narrow island like Japan, and the presence of violent earthquakes there is not strange. The same may be said of the Aleutian Islands and the whole East Indian Archipelago, including the Philippines.

The same reasoning applies to all the South American earthquakes, including those which have destroyed Caracas, Cumana, and other places in Venezuela. This coast lies between the eastern spur of the Andes and the waters of the Caribbean Sea, which is one of the deepest parts of the Atlantic, and the intensity of the subterranean forces is shown by the violence of the volcanic outbreaks in the Lesser Antilles.

§ 54. *Are any earthquakes really tectonic?*

It is held that many earthquakes are tectonic because there is externally only a movement of the strata, as if they were seeking release from strain, and obvious volcanic forces do not appear. Boussingault long ago concluded that many of the earthquakes in the Andes depended on the settling of the strata in these mountains, and this was the beginning of the tectonic theory that most earthquakes are due to collapse or movement for release of strain. To test the validity of this theory, it is advisable to apply similar reasoning to the mountains of a country remote from the seacoast. We choose for this purpose the Rocky Mountains in Colorado, which were formerly near but are now remote from the sea. If what Boussingault witnessed in the Andes was really the settling of the mountains, the same effects ought to be going on in the Rocky Mountains of Colorado. So far as the records of history go, it may be safely said that not a single serious earthquake has ever visited Colorado, and yet many should have been felt if Boussingault's theory of the settling of the mountains is correct. As change is usually ascribed to secular cooling, why should the Andes settle and not the Rocky Mountains? From the absence of earthquakes in Colorado, it is evident that tectonic movements have ceased in that region, though secular cooling has not; and thus we see that these movements after all do not depend on settlement of the mountains due to the shrinkage of the earth. For, if so, it is incredible that the Rocky Mountains can have already attained a perfectly stable position. They ought to be still collapsing like the Andes, since secular cooling is always going on. Thus we see that all earthquakes must depend on underlying explosive forces, and not on mere adjustments of strata to secure release of strain or stability of position, required by the progress of secular cooling.

Another way to reach this result is to recall that the investigation of earthquakes in Hungary, Croatia, Bohemia and other countries shows that most frequently the impulse proceeds from an underlying area of considerable extent, and not from a point nor line, though the surface movement may be chiefly along the nearest fault. If the underlying area from which the shock proceeds is elliptical, as usually happens, we may be quite sure that this diffusion of the impulse over an area indicates an underlying outspread sheet of lava saturated with steam, which finally acquires such tension that it is enabled to shake the overlying crust and cause a movement along the fault lines where the crust is broken and movement is easiest. The lava sheet seeks readjustment, and in the process of equalizing the strain, movement of the molten rock takes place, and the faults not only move vertically, but often also horizontally. This is a natural and simple explanation of fault movement, and it accounts for the rotatory motion so frequently noticed in earthquakes. The great earthquakes of Lisbon, Arica and Iquique have usually been classed as tectonic, but in view of the sinking of the bed of the sea shown by the accompanying seismic sea waves, it is clear that all these terrible disturbances were due to the expulsion of lava from under the ocean.

§ 55. *The geological significance of earthquakes.*

In their new work on "Geology" (Vol. I, p. 534) Chamberlin and Salisbury remark that "Earthquakes are of much less importance, geologically, than many gentler movements and activities. Disastrous as they sometimes are to human affairs, they leave few distinct and readily identifiable marks which are more than temporary." Mention is made of the effects of earthquakes in fracturing the rocks of the earth's crust, but the fractures, it is pointed out, do not show at the surface when the soil is deep. These authors also remark (p. 527) that "the most prevalent (source of earthquakes) is probably the fracture of rocks and the slipping of strata on each other in the process of faulting."

Let us now examine these remarks a little more carefully. If earthquakes are due to fracture of rocks and the slipping of strata, it follows that the forces involved here have played no part in the original formation of the globe, but are the effects of collapse after the mountains were formed. On this view, earthquakes would be of very small consequence geologically, because they are associated only with destructive and not with constructive processes. But is such a view tenable? If earthquakes are not due to the same forces which upheaved the mountains, what other forces besides these have been active in the development of the globe? The only forces of construction now felt upon the earth are those exerted in earthquakes. So far as we can see, no other constructive forces are at work. Therefore, the forces felt in earthquakes are identical with those which formed the mountains, and this is sometimes admitted, though mountain formation itself is assigned to the wrong cause.

Destructive forces such as erosion are wearing down the structure of the globe, while earthquakes are the only known forces which are building it up. We take it, therefore, that so far from being of little importance geologically the forces felt in earthquakes are of the greatest importance, and most of the constructive forces in the development of the earth are due to this cause. The destructive effects of earthquakes are only incidental to the more fundamental constructive purpose which underlies the operation of these forces. When an earthquake occurs rocks in unstable positions fall, loose sediment is shaken down, and other settlements occur, but the real constructive work consists in upheavals, little by little it may be, of mountains, islands, coasts, plateaus and larger areas. These elevations are actually witnessed in certain earthquakes, and could not possibly arise from any processes of collapse. Sometimes these constructive forces work slowly and quietly, but usually with more or less violence; and the usual method of elevation is by the injection of lava saturated with steam.

What has been taken to be the cause of earthquakes, namely, the slipping of rocks, is really the effects of more deep-seated explosive forces. Earthquakes, therefore, are not due to the effects of secular cooling, but to the vapor of steam arising from the penetration of water into the heated layers just beneath the crust. If earthquakes were due to cooling they ought to be as frequent in desert regions as in deep seas along the shores of continents, where they really are abundant.

XI. Earth Tremors and Teleseismic Disturbances.

§ 56. *Slight movements of the earth.*

A great many questions recently have been discussed relating to slight slow oscillations shown by horizontal pendulums and other instruments designed to detect delicate changes of level. No doubt very many of these changes are correctly ascribed to the yielding of the solid earth, due to variable loading of the soil by tidal, seasonal and meteorological influences. But may not others be due to the slow but steadily varying influence of subterranean forces as discussed in this paper? Some of the strains thus constantly arising would be released by microseismic disturbances which show no periodicity or regularity; while others would be cumulative and have at length a small secular effect. The fact that the ground in most places is comparatively so stable under the test of astronomical observations seems to show that these effects usually are slight, except in the neighborhood of the sea; but many small irregular disturbances occur, and it is not improbable that a considerable number of them may have their origin hidden deeper in the earth than heretofore has been suspected. If great earthquakes originate at depths of from eight to twenty miles, we may be sure that the forces there at work produce some surface changes of level even if no violent outbreaks occur.

§ 57. *Humboldt's views on earthquakes.*

In the fifth volume of the *Cosmos* (p. 288) Humboldt justly remarks how Charles Darwin, "with his peculiar generalizing view, has grasped the connection of the phenomena of earthquakes and eruptions of volcanoes under one point of view."

In his "Views of Nature," Vol. I, p. 361, Humboldt alludes to the nearly simultaneous occurrence of volcanic and seismic phenomena in places widely separated, and says:

> "All these phenomena prove that subterranean forces are manifested either dynamically, explosively, and attended by commotion, in earthquakes; or possess the property of producing, or of chemically modifying a substance in volcanoes; and they further show, that these forces are not seated near the surface in the thin crust of the earth, but deep in the interior of our planet, whence through fissures and unfilled veins they act simultaneously at widely distant points of the earth's surface."

And in his "Travels," Vol. I, p. 172–3, he adds:

"Everything in earthquakes seems to indicate the action of elastic fluids seeking an outlet to diffuse themselves in the atmosphere. Often on the coasts of the Pacific, the action is almost simultaneously communicated from Chili to the Gulf of Guayaquil, a distance of six hundred leagues; and, what is very remarkable, the shocks appear to be the stronger in proportion as the country is more distant from burning volcanoes. The granitic mountains of Calabria, covered with very recent breccias, the calcareous chain of the Apennines, the country of Pignerol, the coasts of Portugal and Greece, those of Peru and Terra Firma, afford striking proofs of this fact. The globe, it may be said, is agitated with the greater force, in proportion as the surface has a smaller number of channels communicating with the caverns of the interior. At Naples and at Messina, at the foot of Cotopaxi and of Tunguragua, earthquakes are dreaded only when vapor and flames do not issue from the craters. In the kingdom of Quito, the great catastrophe of Riobamba led several well-informed persons to think that that country would be less frequently disturbed, if the subterranean fire should break the porphyritic dome of Chimborazo; and if that colossal mountain should become a burning volcano. At all times analogous facts have led to the same hypotheses. The Greeks, who like ourselves, attributed the oscillations of the ground to the tension of elastic fluids, cited in favour of their opinion, the total cessation of the shocks at the island of Eubœa, by the opening of a crevice in the Lelantine plain."[1]

§ 58. *Views of Charles Darwin.*

In the "Voyage of a Naturalist," Chapter xiv, Darwin says:

"The forces which slowly and by little starts uplift continents, and those which at successive periods pour forth volcanic matter from open orifices, are identical. For many reasons, I believe that the frequent quakings of the earth on this line of coast (Chili) are caused by the rending of the strata, necessarily consequent on the tension of the land when upraised, and their injection by fluidified rock. I believe that the solid axis of a mountain differs in its manner of formation from a volcanic hill, only in the molten stone having been repeatedly injected, instead of having been repeatedly ejected.

"Moreover, I believe that it is impossible to explain the structure of great mountain-chains, such as that of the Cordillera, where the strata, capping the injected axis of plutonic rock, have been thrown on their edges along several parallel and neighboring lines of elevation, except on this view of the rock of the axis having been repeatedly injected, after intervals sufficiently long to allow the upper parts or wedges to cool and become solid; —for if the strata had been thrown into their present highly inclined, vertical, and even inverted positions, by a single blow, the very bowels of the earth would have gushed out; and instead of beholding abrupt mountain axes of rock solidified under great pressure, deluges of lava would have flowed out at innumerable points of every line."

[1] "The shocks ceased only when a crevice, which ejected a river of fiery mud, opened in the plain of Lelantum, near Chalcis."—Strabo.

This view of mountain formation is essentially identical with that here adopted, except that I conceive the interior part of a mountain, whether a peak or a chain, to be filled underneath with porous lava, which explains the feebleness of the attraction of mountains and the readiness with which they are converted into volcanoes when once their tops are burst open during the paroxysms of an earthquake. The present views therefore confirm and somewhat extend those held by the elder Darwin seventy years ago. In Chapter VI of his "Geological Observations on Volcanic Islands" the great naturalist says:

"Some authors have remarked that volcanic islands occur scattered, though at very unequal distances, along the shores of the great continents, as if in some measure connected with them. In the case of Juan Fernandez, situated 330 miles from the coast of Chile, there was undoubtedly a connection between the volcanic forces acting under this island and under the continent, as was shown during the earthquake of 1835. The islands, moreover, of some of the small volcanic groups which thus border continents, are placed in lines, related to those along which the adjoining shores of the continents trend; I may instance the lines of intersection at the Galapagos, and at the Cape de Verde Archipelagoes, and the best marked line of the Canary Islands. If these facts are not merely accidental, we see that many scattered volcanic islands and small groups are related not only by proximity, but in the direction of the fissures of eruption to the neighboring continents—a relation which Von Buch considers characteristic of his great volcanic chains.

"We ought not, however, to suppose, in hardly any instance, that the whole body of matter, forming a volcanic island, has been erupted at the level on which it now stands; the number of dikes, which seem invariably to intersect the interior parts of every volcano, show, on the principles of M. Elie de Beaumont, that the whole mass has been uplifted and fissured. A connection, moreover, between volcanic eruptions and contemporaneous elevations in mass[1] has, I think, been shown to exist in my work on Coral Reefs, both from the frequent presence of upraised organic remains and from the structure of the accompanying coral reefs. Finally, I may remark, that in the same Archipelago (Galagapos), eruptions have taken place within the historical period on more than one of the parallel lines of fissure: thus, at the Galapagos Archipelago eruptions have taken place from a vent on Narborough Island, and from one on Albemarle Island, which vents do not fall on the same line; at the Canary Islands, eruptions have taken place in Teneriffe and Lanzarote; and at the Azores, on the three parallel lines of Pico, St. Jorge, and Terciera. Believing that a mountain axis differs essen-

[1] A similar conclusion is forced on us by the phenomena which accompanied the earthquake of 1835, at Conception, and which are detailed in my paper (Vol. V, p. 601) in the *Geological Transactions*.

tially from a volcano, only in pultonic rocks having been injected, instead of volcanic matter having been ejected, this appears to me an interesting circumstance; for we may infer from it as provable, that in the elevation of a mountain chain, two or more of the parallel lines forming it may be upraised and injected within the same geological period."

§ 59. *Views of Professor Milne.*

Professor Milne has recently expressed views of somewhat similar character, many of which agree closely with those reached in this paper. In the recent Bakerian Lecture before the Royal Society, he says:

"But if, instead of confining our attention to a relationship between earthquakes, we consider the question of the relief of volcanic strain, many illustrations may be adduced which indicate a close connection between such activities. For example, all the known volcanic eruptions which have occurred in the Antilles, from the first which took place in 1692, have been heralded or closely accompanied by large earthquakes in that region, but more frequently by like disturbances in neighboring rock-folds, particularly that of the Cordilleras. This was notably the case in 1902. On April 19 of that year an unusually large earthquake devastated cities in Guatemala. Small local shocks were felt in the West Indies, and on April 25 it was noticed that steam was escaping from the crater on Mont Pelée, in Martinique. These activities continued to increase until May 8, when they terminated with terrific explosions, submarine disturbances, and the devastation of great portions of the islands of Martinique and St. Vincent.

"The last illustration of hypogene relationship between these regions occurred on Januarv 31 of the present year. On that date a heavy earthquake originated off the mouth of the Esmeralda River, in Columbia. Sea-waves inundated the coast, islands sank, and a volcano erupted. The newspapers of February 2 announced that cables between Jamaica and Puerto Rico had been interrupted, and on later dates it was reported that severe shocks had been felt among the West Indian islands, that six or seven submarine cables had been broken, and that Mont Pelée and La Soufrière, in St. Vincent, were again active."[1]

We have quoted these views of Humboldt, Darwin and Milne in order to exhibit fairly the beliefs of all these great investigators in the development or the possibility of the development of seismic action at a distance when a disturbance is once started.

§ 60. *Teleseismic disturbances.*

From the theory developed in this paper we take is that when a severe earthquake is started at one place the tremors may cause disturbances to spread into neighboring regions or to break out at a distant point if the conditions of the steam pressure underlying

[1] *Proc. Roy. Soc.*, Vol. 77, 1906, p. 374.

the crust are already highly unstable; but there is probably no communication through the depths of the planet, except a wave motion which spreads in every direction, the earth acting as an æolotropic elastic solid, because of the great pressure to which the matter is subjected. In adopting the view that, because sympathetic effects may be aroused at great distances, the disturbances are therefore very deep-seated, Humboldt appears to have been somewhat misled by the ordinary effects of tremors on unstable conditions even at great distances.

Yet there can scarcely be any doubt that the connection of the Andean trough from Valdivia to Guayaquil is so intimate that a disturbance once started under parts of it may easily be propagated over the whole length of this great trough, or even to another part of the globe; and thus we conclude that seismic activity easily extends, and has a widespread effect which was formerly supposed to be transmitted through the deep interior of the earth. It is impossible to doubt that Charles Darwin was entirely correct in concluding that a subterranean connection generally exists between a continent and its outlying islands, for both are often on the borders of the same continental trough. Occasionally the extent of this connection may be even wider, and sometimes cover a whole region or run from one region into another, as in the events mentioned above by Professor Milne; but the disturbances are transmitted principally by waves and by strains through the crust, and not by means of any currents through the deep interior of the earth. As regards the general question of slight disturbances bringing on greater catastrophes when the conditions of subterranean steam pressure are already highly unstable we may go even further. We occasionally read in History of the West Indies, especially the group including St. Vincent, Martinique, St. Lucia, Guadaloupe, Barbadoes and Trinidad, being visited by a terrible hurricane, followed by an earthquake and a "tidal wave"; so that it seems as if all the worst elements in nature were suddenly let loose to devastate these islands. In view of the cause assigned in this paper, it is evident that unstable conditions of subterranean steam pressure may not require anything more violent than the raging of a hurricane to bring on an earthquake, which in turn may be followed by a "tidal wave," for the reasons and in the manner above explained; and thus to the afflicted inhabitants all nature seems to be convulsed at once. From the observed course of events, we cannot doubt that this connection actually exists; and unfortunately it seems to be abundantly illustrated in the annals of the East as well as of the West Indies.

In the same way we explain Alexis Perrey's well-known laws of earthquakes. The forces assigned to account for these disturbances, however, are not the cause of the convulsions of nature, but only the occasions for outbreaks of highly unstable conditions depending on subterranean forces easily set off.

In like manner the violent outbreak of a volcano or the occurrence of a great earthquake in one part of the world may tend to bring on similar phenomena in another remote region.

The order of events often observed in the development of the volcanic and seismic phenomena following great outbreaks seems to support this view. While we do not regard it as proved that an eruption like the recent great outbreak of Vesuvius, for example, could indirectly bring on the earthquake in California and other similar disturbances, yet we do not regard such an influence as at all impossible. Conditions of instability once existing are contagious and tend to spread like a conflagration. As there are on the average over 60 world-shaking earthquakes every year, or more than one a week, it is evident that if one should break out in a region where it might accelerate the outbreak of others, several might be grouped into a small space of time, and these in turn might exercise wide influence on unstable conditions throughout the world, as often seems to be the case.[1] Our knowledge of these teleseismic effects, however, is still far from complete, and the settlement of the question must be left to the future.

§ 61. *Internal state of the earth.*

The investigations of Lord Kelvin and Professor Sir G. H.

[1] In his "Journal of Researches during the Voyage of the Beagle," 1845, p. 291, Charles Darwin mentions this remarkable coincidence of phenomena: After a long slumber, Conseguina in Central America, and Aconcagua and Corcovado (S. lat. 32¾° and 43½°) in Chile, broke out the same day! His suspicion that this coincidence was not accidental would be confirmed by our knowledge of the Andean trough, in the line of which all these volcanoes are situated.

Darwin have shown that the earth is highly rigid, and in a recent paper on the rigidity of the heavenly bodies (cf. *Astron. Nachr.*, No. 4104) the writer has shown that no motion of currents deep down in our planet is really possible, because of the enormous friction due to the pressure at great depths. Thus no currents of fluids or gases exist in the earth, except just under the crust where the explosive strain is terrific. And even near the surface, where the lava is forced to move under the thin crust, in the building of mountain chains like the Andes, the motion is usually accomplished only by the dreadful paroxysm of an earthquake, which expels the molten rock from under the bed of the sea. The suspicion of Capt. Fitzroy and Charles Darwin that in the three months following the earthquake of 1835 the Chilean coast partially subsided to its former level seems not only possible, but extremely probable. Under great strain the viscous mass may have yielded somewhat, and thus there may have been a slow creeping tendency towards the former level.

Judging by the thickness of the sides of Aconcagua, Cotopaxi and other typical volcanoes of the Andes, one would probably be justified in concluding that the thickness of the crust under which the lava moves when expelled is not less than five miles, and it may be as much as fifteen or twenty, but ordinarily it could not well lie outside of these limits. For if we suppose it to be thicker, the leakage of the water would present greater difficulty if the temperature is low; and such thickness would not be required if adequate steam developed nearer the surface. On the other hand, the thickness could hardly be much less than ten miles without enfeebling the layers which must support great strain in the expulsion of matter from the broad trough of the ocean bed. The most probable thickness is from ten to twenty, and for most purposes we shall be safe in adopting the simple mean of fifteen miles.

There are other considerations which lead to substantially the same conclusion. It is found for example by the critical investigation of great earthquakes that most of these disturbances proceed from an average depth of something like ten to fifteen miles. Now, if the theory here developed be admissible, it will follow that these disturbances usually are in or near the lower stratum of the earth's crust, which thus fixes the thickness of the layer at about the same figure. It will be evident from this consideration and others that the thickness of the crust is by no means uniform throughout the globe. Determinations of the depths of large earthquake disturbances are probably the best means of approximating the thickness of the earth's crust, since data of this kind depend wholly upon observation and are indepenedent of any hypothesis.

XII. Conclusions.

§ 62. *Summary of results.*

1. We have seen that deposits of sediment on the continental shelves could not possibly produce anything but the most gradual increase of weight on these portions of the earth's crust; and since such rocks as marble are proved to be fluids of great viscosity and therefore capable of slow secular bending without rupture, we may feel sure that any stresses thus arising in the earth's crust would be relieved by gradual yielding, and that no violent earthquake shock could ever arise from such a cause.

2. The theory that earthquakes are due to fracture and slipping of rocks is disproved by the great depth (ten to twenty miles) at which world-shaking earthquakes are found to originate, and by virtue of the fact that they come not from a point nor from a line, but from an area; and moreover earthquakes follow the seashore, seldom occurring far inland, and never in desert countries, though abundant in the bed of the ocean.

3. It therefore follows that earthquakes must depend upon explosive forces within or just under the earth's crust, and frequently spread over a considerable area, and the preponderance of disturbances in the sea and along the shores of continents shows that the forces depend in some way upon the sea water. These explosive forces can be best studied in connection with the eruption of volcanoes, since volcanic outbreaks are also accompanied by earthquakes often felt over large areas.

4. Not all earthquakes lead to eruptions, but if the shocks in a given region cease on the eruption of a neighboring volcano, we may feel sure that the forces producing the eruption also produced the antecedent earthquake shocks felt by the surrounding country.

5. That steam is the cause of volcanic eruptions is proved by the

distribution of active volcanoes about the seashores and by the innumerable eruptions which occur in the depths of the ocean, whereas such vents always die out inland; and moreover by the fact that of the vapors emitted from volcanoes 999 parts in 1,000 is estimated to be steam, the remaining one-thousandth part being by-products incidental to the moisture and high temperature.

6. The *vera causa* of volcanic action and of certain earthquakes thus established for some particular cases must be held to be the universal cause in all cases whatsoever, according to Newton's rule of philosophy.

7. The heaving of steam accumulating within or just beneath the earth's crust is therefore the true cause of all world-shaking earthquakes, and volcanic outbreaks occur only when an outlet is forced through to the surface, which usually happens in mountains, where the earth's crust is already badly fractured and upheaved.

8. When the subterranean steam pressure becomes great enough to shake the earth's crust, it naturally moves at the nearest fault line, where the rocks are broken, *but the movement observed is the result, not the cause of the earthquake.*

9. Volcanoes are particular mountains blown open by steam pressure under the throes of earthquakes (cracks in the rocks appear to be the beginning of some few volcanoes), and since all volcanoes blow out pumice and ashes, these materials must be held to exist in all mountains, and are made by the inflation of molten rock with steam and other vapors.

10. Any mountain peak, therefore, is capable of becoming a volcano if the subterranean steam pressure be sufficiently powerful to break open an orifice. But orifices close up and volcanoes die out inland and elsewhere if the supply of steam is inadequate to keep open the vents upon which the activity depends. Even if stopped up for a time later heaving of the earth may give the volcano renewed activity, and when the mountain has been dormant for a long time it is found that the violence of the eruption is greatly increased. The violence of the subterranean pressure in such a case approaches that of a region which has no vent at all, and hence we see why earthquakes in non-volcanic regions frequently become so terrible, because the forces accumulate to frightful fury before any

relief whatever is afforded, and the result is a most terrible earthquake.

11. The mountains are formed by the injection of steam-saturated lava under the coast, which breaks the overlying surface rocks and gives rise to a ridge parallel to the sea. This is why all mountains are formed parallel to the seashores.

12. By continually injecting the land with lava from under the bed of the sea the coast is raised and the mountains upheaved, and some of them usually break out into volcanoes; while at the same time the support of the sea bottom is undermined by the thinning out of the fluid substratum, and at intervals the bottom sinks down to restore stability.

13. The sinking of the sea bottom in this natural process of earthquake injection of the land is the cause of that class of sea waves found to follow violent earthquakes, in which the water first withdraws from the shore and then returns as a huge wave. Those waves noticed to rise suddenly without previous recession of the water usually are due to submarine upheavals and eruptions in the bed of the sea.

14. Islands are built up by injection from the sea, and hence have their mountains as veritable backbones, because the injection is symmetrical from both sides. In many cases the sea bottom is thus undermined and finally sinks down, making a hole beside the island, or a trench. The fact that all islands are not accompanied by such sinks is no argument against the theory, because the subsidence has not always taken place; it is the occurrence of even a considerable number of such sinks beside islands which proves the validity of the theory. Such intimate associations between elevation and depression could not be the result of chance.

15. In the repair of ocean cables broken by earthquakes, subsidence of the sea bottom is frequently found to follow these disturbances. This is a direct observation of the above effects in certain cases which are established by actual measurement, the subsidences frequently amounting to hundreds of fathoms.

16. The sea bottom does not subside without the lava under the crust being forced out into some other place, as into islands, submarine ridges, or shores; none of this movement is due to the

secular cooling of the earth, but is all to be explained by the undermining effect of steam accumulating under the earth's crust.

17. Mountains in the interior of a dry country, as the Rocky Mountains in Colorado, exhibit no important movements, while those on the coast, like the Andes, are always heaving. This shows that the sea is the cause, and not the secular cooling of the globe, which is wholly insensible.

18. The only countries which are free from earthquakes are the deserts, and therefore practically uninhabitable; there is accordingly no escape from earthquakes, and buildings designed for permanency should be framed to withstand them without material injury.

19. While in the long run the elevation of the land predominates, there is also subsidence, due to the non-concurrence of the forces in certain regions beneath the crust. It is idle to deny these oscillatory movements of the crust, and many good illustrations of both are clearly established. Every island which is thrown up in the sea is a witness to one of the most general laws of nature.

20. As water is taken up in the crust both in the crystallization of rocks and in the processes of earthquake movements, and only a part of this vapor is restored to the surface through volcanic action, there is a secular desiccation of the oceans, but the process is excessively slow and not certainly recognizable during the historical period, though a part of the lowering of the strand line in later geological ages is no doubt traceable to this cause.

21. The elevation of the plateaus depends on the same cause which upheaved the mountains; and all plateaus, like the mountains, are underlaid with various forms of pumice, which accounts for their feeble attraction as shown by geodetic observations.

22. No doubt various chemical changes go on under the earth's crust where the water has penetrated the lava and the steam becomes superheated, but the predominance of water vapor in volcanoes shows that the other gases are only by-products, incidental to the moisture and great heat. Dissociation of water vapor is one of these effects.

23. The details of mountain structure admit of explanation on the present hypothesis, while heretofore no such explanation was forthcoming. A theory which accounts for the position of the

ranges relatively to the sea, the slopes of the ranges, and the side spurs, and the relation of mountains to earthquake and volcanic phenomena, should have a strong claim to acceptance. This theory was partially foreshadowed by the Arabian astronomer Avicenna, in the tenth century of our era.

24. The theory of the penetration of sea water into the crust of the earth and its connection with volcanoes and earthquakes dates back to Lucretius and Aristotle, while the upheaval of the land is distinctly announced by Strabo. We have, therefore, been simply verifying and extending the impressions of the ancients formed from the general aspects of nature long before the sciences had become exact.[1]

§ 63. *General considerations.*

[1] Since finishing this paper the writer has been much impressed with the following passage in the article *Poseidon, Encyclopedia Britannica,* ninth edition:

"Poseidon, the ancient Greek god of the sea and of water generally. . . . He was the god of navigation, adored by all who sailed the sea. His temples stood especially on headlands and isthmuses. As god of the sea he disputed with other deities for the possession of the land—with Athene for Athens and Troezen, with Helios for Corinth, with Hera for Argos, with Zeus for Aegina, etc. Earthquakes were thought to be produced by Poseidon shaking the earth,—hence his epithet of 'Earth-shaker,' and hence he was worshipped even in inland places, like Apamea in Phrygia, which had suffered from earthquakes. Hence also may have arisen the custom in some places of sacrificing moles to him. The great sea-wave which often accompanies an earthquake was also his work; the destruction of Helice in Achaia by such a wave (373 B. C.) was attributed to his wrath. Once when an earthquake shook the ground where a Spartan army was encamped, the whole army sung a hymn to Poseidon. The island of Delos was thought to have been raised by him from the bottom of the sea, and in 237 B. C., when a new island appeared between Thera and Therasia, the Rhodians founded a temple of Poseidon on it. Thessaly was said to have been a lake until this god opened a way for the waters through the Vale of Tempe. Poseidon was also the god of springs, which he produced by striking the rock with his trident, as he did on the acropolis of Athens when he was disputing with Athene for the sovereignty of Athens. This dispute was represented on the western pediment of the Parthenon. . . . There were collossal statues of him at Helice in Achaia, on the Isthmus of Corinth (set up by the Greeks after the Persian wars) and at Tenos."

It is very remarkable to find that at an early age the Greeks had so directly connected earthquakes with the sea, probably through the seismic sea waves, which they often observed in this part of the Mediterranean. (Note added December 17, 1906.)

The way in which several different classes of phenomena find explanation by the most simple of causes may be considered not the least remarkable result of the present investigation. In the minds of those who follow Newton's first rule of philosophy, "to admit no more causes of natural things than are both true and sufficient to explain their appearances," this will probably tell strongly in favor of the truth of an hypothesis which explains easily and naturally such diversified phenomena as earthquakes and volcanoes, the formation of mountains and the deficiency in their attractions, the origin of cordilleras from the ocean trenches near continents, and of the great sea waves which frequently accompany violent earthquakes. But there will doubtless be others who will prefer a variety of causes, and will be slow to believe that the laws and order of nature are so simple.

In an investigation of such considerable extent it would not be surprising if many difficulties should require further elucidation than they have received in this imperfect outline; for the writer has not the geological learning required for the full treatment of many of the great problems of the earth's crust. But if, on the one hand, some defects or omissions should be found, and no doubt many of them will appear in special branches of the extensive lines of thought here traversed, may it not be thought, on the other, that the harmony established with geodetical measurements on the attractions of mountains and the deviations of the plumb line, combined with the explanation of the equilibrium of the terrestrial spheroid between the land and water hemispheres, is not wholly without a certain degree of compensation to those interested in the numerous and related problems of the physics of the earth?

That the existing theory of earthquakes and volcanoes and mountain formation is embarrassed by many difficulties has often been frankly admitted. While the theory here suggested may require extension or modification, one may confidently submit the question whether it is really possible to doubt its essential truth.[1]

[1] The sinking of the sea bottom after great earthquakes have heaved up the coast, as along the west shore of South America, furnishes a truly remarkable criterion for unraveling the unseen processes of nature, hidden beneath the earth's crust. The sea bottom could not sink unless it was in some way undermined, and the adjacent coast could not be upraised unless

If this inference should prove to be well founded, may it not be possible to conclude the contest long waged between astronomy and geology with credit and advantage to both of these great sciences? For it seems to be proved that owing to the great pressure acting throughout the earth's interior, and the solidity of the rocks which cover its surface, the terrestrial spheroid, when subjected to great strain, behaves and vibrates as an æolotropic elastic solid; yet the fluid medium long contended for by geologists to explain crumplings and foldings of the crust is really found to exist or develop in a thin layer just beneath the outer crust, and we have explained its simple and somewhat automatic mode of operation. On several grounds it appears that this layer is extremely thin, certainly not much thicker than the crust itself; and, moreover, it too remains essentially quiescent and rigid, except when set in motion by the recurring paroxysms of steam pressure seeking release, which gives rise to an earthquake and the movements of molten matter essential to geological processes. The original conceptions of astronomy are thus apparently verified, while at the same time the long-standing needs of geology are amply met. And although no effort has been made in this paper to harmonize the conflicting views long prevailing in the two sciences, it would seem that this unexpected result may prove to be not the least interesting among several conclusions respecting the constitution of the globe.

something was pushed under it: both these movements are observed to occur, and always in the same order. Along the shore, just parallel to the sea coast, the crust is pushed upward to form mountains, while the adjacent sea bottom is correspondingly sunk down. Can anyone doubt that we have here a true cycle of events? One of these events necessitates the other, and all are so connected that one can begin at either end of the chain of phenomena and reach the other. Thus, if we begin with volcanoes we are led downward through these vents to the earthquake and mountain forming forces at work under the surrounding land; and finally we come out beneath the ocean where world-shaking earthquakes and seismic sea waves originate. On the other hand, if we begin with seismic sea waves, we are led downward through the observed subsidence of the sea bottom and pass under the crust to the mountains raised along the coast, by earthquakes occurring mainly under the sea, and thus finally reach the volcanoes at the top of the range, erupted by the pressure of subterranean steam, and blowing out lava, pumice, ashes, and vapors. All the grandest phenomena relating to the earth's surface are thus connected in an endless chain or circuit. Could such perfect order and harmony be established among all these varied phenomena without the discovery of the true physical cause? (Note added December 3, 1906.)

The details of the processes involved in the elevation of continents, and just how these great land areas originated, are yet to be worked out, and appear to be involved in considerable obscurity, most probably connected with the terrestrial origin of the moon. Perhaps our knowledge is still too incomplete for a satisfactory attempt at this inquiry; but it seems not improbable that the lines of thought here struck out may eventually prove fruitful of further discovery.

§ 64. *Origin of the present investigation.*

It will be seen from the foregoing account that the present investigation grew out of the difficulty of explaining satisfactorily the rotatory motion of the San Francisco earthquake. When the writer very soon became convinced that the accepted theory, which explained these phenomena by dislocations, subsidences and faults, was not well founded, the investigation was extended little by little till it covered a number of important natural phenomena not usually correlated. The order in which this extension took place is perhaps of no importance, but to enable anyone who might be curious to understand the original line of thought, it may not be wholly out of place to mention that the next step was to assign the explosive activity of volcanoes to steam; and then the traditional reasoning about these vents being safety valves was intelligible, and it became clear why violent earthquakes do not predominate in volcanic districts and why large tectonic earthquakes are always so violent.

While considering the mode of release of steam pressure in tectonic earthquakes, where the strata are unbroken, I was led to inquire into the origin of mountains. The only explanation I could find was by the theory of contraction producing folding along lines of weakness in the earth's crust. It seemed to me remarkable that the lines of weakness should nearly always follow the coast lines of continents. Such an arrangement should not occur by chance. It was easy to grasp the connection of earthquakes with volcanic activity when the volcano is once formed; and the question naturally arose, how did the volcanoes and mountain chains originate? I recalled that volcanic islands are always being thrown up, and numerous islands had been formed in this way on the bed of the sea, which are mountains under water. On the other hand most geological theories regarded the mountains as formed in the past, while it seemed to me that some of the mountains are near enough to the seashore to be still in the process of upheaval. In reflecting over these questions, on May 20th, I recalled, from impressions obtained at the Coast Survey in 1899, that some of the islands in the sea had depressions on the side of them as if the material had been thrown up from the adjacent bed, and that deep trenches in the oceans also ran parallel to the great ranges such as the Andes. I noticed also that the volume of the Andes and of the islands were severally not very far from equal to those of the adjacent trough and sinks. Could it be possible that the Andes also had been raised by matter pushed up under the crust from the bed of the adjacent oceanic trough? On recalling that the sea bottom near Pelée has been found by observations to have actually sunk after the great ejection of ashes and vapors in 1902, and that the hollow form of the Andean trough would prevent vertical eruptions from beneath, and cause any explosions which might originate under it to seek release at the sides, thus pushing up the mountains through columns or rather layers of lava advanced little by little, by "lateral thrusts," as the geologists say, from under the sea, I did not hesitate to conclude that the Andes had originated in that way. The existence of the long trough, so deep and so exactly parallel to the mountains for so great a distance, proved it; and it was easy to see also that later the resistance toward the land side would become so great, owing to the great distance and height of the mountains, that release would eventually come more easily by the other side of the trough folding up into a parallel range, which would thus emerge from the sea as the New Andes, and eventually cause a further recession of the west coast line of South America.

The provisional entertainment and private acceptance of these views seemed daring enough, but it appeared to me there was no escape from them. On the following day, May 21, I recalled that geodetic observations indicated a feebler attraction for mountains than if they were solid and of the same mean density as the crust; and it was evident that my earlier conception of pumice-filled cones and chains had not been altogether too rash. The rest of the work consisted in nothing but verification and elaboration of these intuitions.

Moreover, the cause of the great sea waves was now perfectly clear. It was impossible to doubt that these phenomena, of the class in which the water recedes from the shore in the first few minutes following an earthquake, generally arise from a subsidence of the sea bottom after the expulsion of porous lava in the natural process of elevating the mountains and coasts.

After these ideas had been worked out in such a way as to establish harmony among the widely diversified phenomena it was gratifying to find that such views were not inconsistent with the thoughtful remarks of Humboldt, and that Charles Darwin seventy years before had reached conclusions in most respects remarkably similar. It seemed, therefore, justifiable to suppose that the process of mountain formation thus outlined and verified was in all probability the correct one. Such was the order of the writer's thought, which he records with reluctance and hesitation, but chiefly in the hope that it may not be wholly without value to others.

In the final arrangement of the paper it was deemed best to introduce the citations from Humboldt and Darwin under the discussion of the several topics rather than as extremely long foot-notes. And this arrangement was the more agreeable on account of the great esteem in which the writer has always held these illustrious investigators. As Professor Milne is justly recognized to be the most eminent living authority on earthquakes, to whom we owe extensive international coöperation and the present widespread interest in the subject, which has contributed so greatly to the advancement of our knowledge, the same principle has naturally been employed in the exposition of the results of his researches.

While it is impossible to estimate too highly the great strides recently made in seismology under the leadership of Professor Milne, Dr. Davidson, Montessus de Ballore, Major Dutton, Von Rebeur-Paschwitz, Dr. Agamennone, Dr. Rudolph, Professor Omori, and others, who have reduced seismology to a science of precise observation and measurement, it is perhaps unfortunate that the views of Humboldt and Charles Darwin as to the causes involved in earthquakes were ever abandoned by modern investigators, though this probably has not retarded the progress of observation and experimentation on the constitution of the globe.

In certain respects the theory here outlined may be capable of observational tests. The importance of the subject would appear to be such that it may be worthy of consideration whether geodetic investigators of the different nations might not advantageously arrange to establish earthquake and tidal observatories and more precise levels on coasts such as those of Chili, Peru, California, Japan, Italy, Greece and other countries, for the more exact study of progressive secular movements. Has not the time come to test geological and seismological theories by the accumulation of exact empirical data, and is not this a debt which we of this generation owe to the future?

§ 65. *Seismic activity a maximum along the coasts of deep seas and a minimum in the great inland deserts.*

If the cause assigned for the explanation of earthquakes be confirmed by time and experience, it is evident that no place on the earth can be said to be wholly removed from the danger of these disturbances; yet the dangers will be a maximum on the coasts of deep seas where the shores are of leaky character and the troughs are at work,[1] and grow less and less along the coasts of the shallower waters where the troughs are absent and the stratification of the rocks is more secure. Thus northern and central Europe and the eastern coast of the United States are comparatively safe. Yet sooner or later, but fortunately to be reckoned in many cases by intervals of thousands of years, every place (except the great inland deserts which are nearly uninhabitable) is likely to be shaken by an earthquake of considerable severity; and those works of man which are to be preserved and to stand through the centuries should be built accordingly.[2] The great layer of water covering the earth,

[1] In his thoughtful article on "Geology," *Encyc. Brit.*, p. 255, Sir Archibald Geikie justly remarks: "Some of the most terrible earthquakes within human experience have been those which have affected the western seaboard of South America." The cause of this is now plain, viz., the Andean Trough is probably the largest and most powerful in the world. And in general the seimicity of a region in the production of world-shaking earthquakes depends on the extent and power of its ocean troughs.

[2] Humboldt laments the destruction wrought by earthquakes upon works of art, architecture, monuments and inscriptions of the classic period, which were developed in a region of such high seismic activity as to render their preservation difficult.

which gives life to animals and plants, and in the form of steam is the greatest mechanical agent of man, when sunk into the crust becomes also one of his worst destroyers, on account of the explosive vapor generated beneath by the internal heat of the globe.

Finally, it may not be without interest to note that, so far as our knowledge extends, the earth alone among the encrusted planets of the solar system has an abundance of water and mountains, with volcanoes and earthquakes. Mars seems to have only a trace of water and no sensible mountains or volcanoes. And while Venus is largely obscured from our view, the chances are that its veil is due to clouds, indicating an abundance of water, and hence that its conditions of evolution may approach those of the earth.

Blue Ridge on Loutre, Montgomery City, Missouri,
September 23, 1906.

Note.—For kind permission to use Figs. 6, 7, 8, and 9 we are indebted to the courtesy of Rand, McNally and Co., of Chicago.